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Project Report

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Effect of drilling process on hole quality, delamination of CFC

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Summary

Defects during the drilling process in carbon fibre laminates can result in late stage rejections in the aerospace industry. This project shows a comprehensive analysis of the influence of drilling parameters on hole quality and delamination. Also, optimum drilling conditions are presented.

Drilling at different parameters with both drills uncoated and coated allowed the examination of the impact of the drilling parameters and the drill's coating on the results. Although during the machining unexpected high temperatures damaged the top surface of the work-piece, measurements of peel-up delamination at the holes entrances showed that it was improved by using a high feed rate and a low spindle speed. Push-out delamination could not be measured due to the poor quality of the holes exits. The overheating and the poor hole quality at the exits of the holes were mainly caused by the drill's geometry, which was proved to not be the most adequate for the job. Drilling parameters also influenced both problems, which were increased when a low feed rate and a high spindle speed were used. In these same conditions the drills suffered the most wear and damage too. Although the drill's coating showed no impact on delamination or hole quality results, it was an effective solution regarding tool wear.

A second study regarding drilling conditions was carried out to improve the overheating and the poor holes quality achieved at the exits in the first study. The results showed that the use of coolant avoided high working temperatures and the use of a sacrifice board led to clean exits in where the delamination factor could be calculated.

It has to be noted that this project was developed between weeks 3 and 10 of the Spring semester, as the project assignments were on February 13th.

In addition, due to mistakes made by the company from where the drills for the project were purchased, the delivery of the tools took over one month (ordered on March 17th, delivered on April 24th).

Contents

Nomenclature

Symbols:

F_A	applied thrust force [N]
q	contribution of chisel edge on the applied thrust force [N]
f	axial feed [mm/rev]
n	spindle speed [rpm]
f_r	feed rate [mm/min]
v_c	cutting velocity [mm/min]
D	drill diameter [mm]
D_{MAX}	maximum diameter of the damage zone [mm]
F_d	delamination factor [no units]

1.0 Introduction

Due to their high strength-to-weight ratios compared with metals, composite materials have been increasingly used in the aerospace and military industries, and more recently in the sports and leisure business.

Although a lot of research is being done, the level of understanding of composite materials' properties and behaviour, as well as their processing technology, are not as developed as with metals yet.

Focusing on the aerospace industry, carbon-fibre reinforced composite laminates are extensively used for structural purposes. Even though the composite structures are manufactured near-net shape, some secondary machining processes are needed, with drilling being one of the most frequently applied, mostly for assembling requests.

Anisotropy is an important particularity of long fibre composites, with their mechanical behaviour being different along the fibre direction than in the perpendicular direction. In fibre composite laminates, another degree of anisotropy is also introduced by their weak inter-ply interface. It is not common to cause loads along their weak direction, though drilling processes usually introduce forces in the drilling direction.

Among the main damages caused by drilling to the laminates there is delamination, chip-out of fibres and matrix, matrix overheating, fraying, burring, hole surface roughness and tool wear, delamination being the most critical one. Apart from the laminate's load capacity, these induced defects can affect other major mechanical properties such as strength, stiffness and fatigue. For instance, 60% of all part rejections during the final assembly of an aircraft are due to drilling-associated delamination [1].

The optimisation of these secondary machining processes such as drilling is vital, as rejections on the last stages have a huge impact in terms of cost and time.

The aim of this project was to assess the influence of drilling parameters on delamination and holes quality, as well as find optimal drilling conditions. In addition, the benefits of using a coated drill are presented.

2.0 Literature review

The drilling process is one part of the so-called machining processes, which are characterised for being industrial processes in where the work-piece is shaped by removing the unwanted material. Drilling is classified as one of the traditional chip-forming processes together with turning, boring and milling [2].

Although in metal cutting the material is removed as a plastically deformed chip of considerable dimensions, in the case of fibre reinforced composites the removal is by fracture [3] and the chips are powder-like [4].

In order to produce holes, during the drilling, the cutting tool called "drill" rotates by the spindle of a machine and an axial movement pushes it forward into the work-piece. Process parameters such as axial feed and spindle speed, work-piece and tool materials, tool geometry and process conditions such as cooling, influence and characterise each drilling process.

Regarding the drills' geometry, it is very complex. Although their consistency and repeatability has increased over the years, this complexity has always limited their accuracy. Also, it has hindered the introduction of new tool materials in comparison with the turning and milling processes. The most commonly used materials for making the drills have been HSS (high-speed steels), HSS-Co and solid WC (tungsten carbide, commonly known as "carbide"). The acceptance of the carbide drills has represented the greatest improvement in productivity. In comparison with an HSS drill, the productivity is increased by a factor of 2 to 10 by using a carbide drill. In addition, the hole quality is also improved. In general, greater drill's rigidity improves the drilling operation [2]. Early studies have shown that using HSS drills for drilling carbon fibre composites is the least suitable alternative as they exhibit extreme levels of tool wear [5].

Specifying on composite laminates, their drilling process has been extensively studied with interesting and useful conclusions having been reached so far.

As previously stated, among the laminate's damage shown after the drilling operation, delamination is the most critical one. Delamination can be an outcome of two different types of damage mechanisms that do not have the same cause. In the entrance of the hole, peel-up delamination (Figure 1a) can take place if cut materials are pushed up the drill flute. Caused by the cutting forces, an upward peeling force is introduced and tends to separate the upper ply from the uncut material held by the thrust force. It can be avoided using low feed rates [6]. The other type of delamination it is known as push-out delamination (Figure 1b). This type of delamination is caused mainly due to the drill's thrust force. As the drill is nearing the exit plane, the uncut thickness to withstand the thrust force decreases so the plies close to the exit hole are more likely to suffer this kind of delamination.

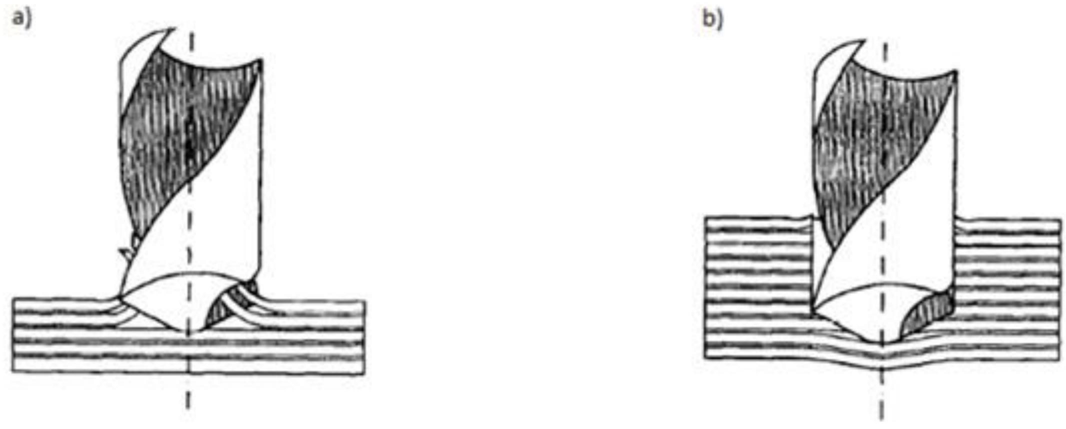


Figure 1. Peel-up delamination (a) and push-out delamination (b) [7]

Some mathematical models based on linear elastic fracture mechanics and classical bending plate theory have been proposed in order to find the critical values in which the load exceeds the interlaminar bond strength and push-out delamination begins to occur. A model developed in 1990 by Hocheng and Dharan [8] predicted that thrust force's critical value. In 1997 Tsao and Chen [9] developed the model in order to be able to determine the location of delamination. Later on, in 2001, Zhang et al. [10] published another model more developed in which it determined the critical thrust force for each ply of the laminate, even for multidirectional laminates.

A recent and more economical alternative is the use of finite element models (FEM) to determine computational models in order to predict stresses, strains and deformations in the work-piece during drilling. In recent times, numerical predictions of critical thrust force's values and delamination have been performed in drilling of composite laminates [11-13].

Thrust force has been found to be influenced by drilling parameters such as the feed rate and the spindle speed. Among the different drilling parameters, it has been observed that feed rate is the one that has the greatest influence on thrust force. Several studies report that with low feed rate and high spindle speed values, delamination becomes less liable to occur [6, 10, 14-21]. However, a study carried out in 1996 by Lin et al. [20] at high speed showed that drilling at high spindle speed increases tool wear which as it is explained below, leads to a rise in thrust force.

Moreover, some machinability maps have been developed in order to provide quick optimal solutions depending on different process parameters [15, 19].

Tool wear has also a great influence in delamination [7, 14]. Chisel edge (Figure 2) contribution to thrust force has been proved to be around 50% [22].

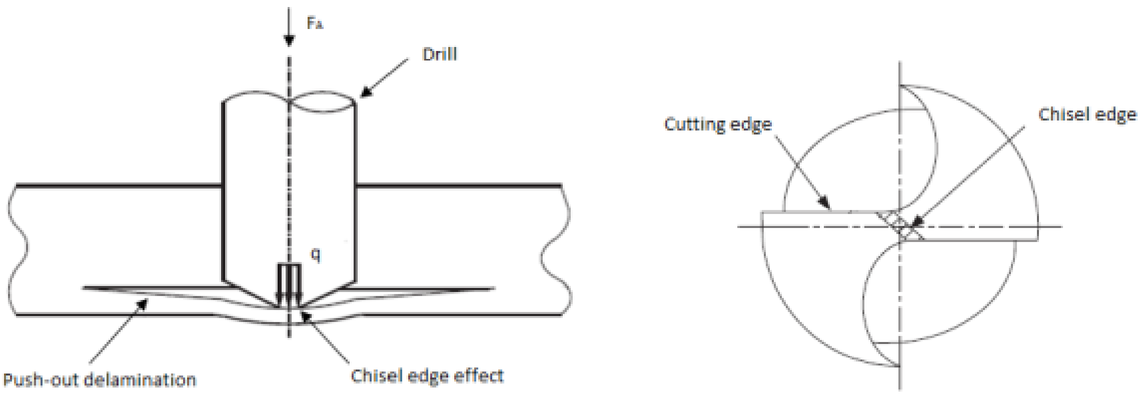


Figure 2. Chisel edge effect [14]

With wear the chisel edge effect produced by the stationary tool centre increases and consequently so does the thrust force. Won and Dharan [23] showed in 2002 that the use of a pilot hole removed part of the chisel edge effect, which allowed drilling at higher feed rates without delamination occurring. Also, the use of a hard-cut coating has been reported to reduce wear and hence thrust force [24]. However, tool wear depends on many factors like the type of tool, work material, drilling conditions and the use of lubricant. High feed rate would reduce this problem, though it would induce push-out delamination.

The temperatures during the operation also influence the result. High temperatures due to the friction between the tool and the work-piece increase tool wear and can induce matrix overheating. This could soften the matrix making it sticky and producing clogging. High spindle speeds and low feed rates enhance the temperatures to rise during drilling. Preventative measures that can be applied are the use of a vacuum system to clear out the cut material and the use of coolant.

Hole surface roughness, though it does not have a significant impact in the mechanical properties of the laminate, is an important criterion to validate the quality of the machining process. It has been shown that low feed rates and the use of a hard-cut coating do reduce this imperfection [24].

As previously said, tool geometry is another main factor to be considered in the drilling process. There is a wide range of different drill forms, dimensions and tolerances. The best type of drill for a given application depends on several factors such as the work material and the hole characteristics. Among the many different types of drills, twist, step and core drills should be mentioned. For economic reasons among many others, twist drills (Figure 3a), so called because of their helical channels – flutes – for chip evacuation along their body, are the most common used and vary widely in their geometries [2]. On the other hand, step drills (Figure 3b) have been reported to perform great in composite laminate drilling, as their geometry allows smaller chisel edge effect and hence less thrust force, which is further reduced with a higher stage ratio [25]. Core drills (Figure 3c) also cut more efficiently than other conventional drills mainly because there is no stationary tool centre, which reduces axial force [7].

a) b) c)

Figure 3. Different tool geometries: twist drill bit (a), step drill bit (b) and core drill bit (c)

Other types of drills such as the dagger drill [6, 7] have also been used in different comparative studies showing again that the geometry of the tool has a great influence in thrust force and in the damages caused by the drilling process.

About geometrical characteristics, research indicates that a custom-made drill for composite laminates should have a downsized chisel edge to reduce push-out delamination risk and a small rake angle in order to minimise peel-up delamination risk [26]. However, a small or neutral rake angle will hinder chip evacuation and could eventually cause material build-up on the cutting edges, especially in soft materials [2]. Also, for abrasive materials such as carbon fibre composites smaller than 118º point angle's drill bits are recommended [21].

With all this information taken into account, the experimental programmes for this study were developed.

3.0 Experimental programme (first study)

The tested work-piece used in this study was a 19mm thick (80 layers) carbon fibre epoxy laminate supplied by Airbus. The layers were unidirectional prepregs (Hexcel HEXPLY UD T700 268 M21 34% T700-M21) with a nominal fibre volume fraction of 59%. The stacking sequence was [90/45/0/-45] so as to get a quasi-isotropic laminate.

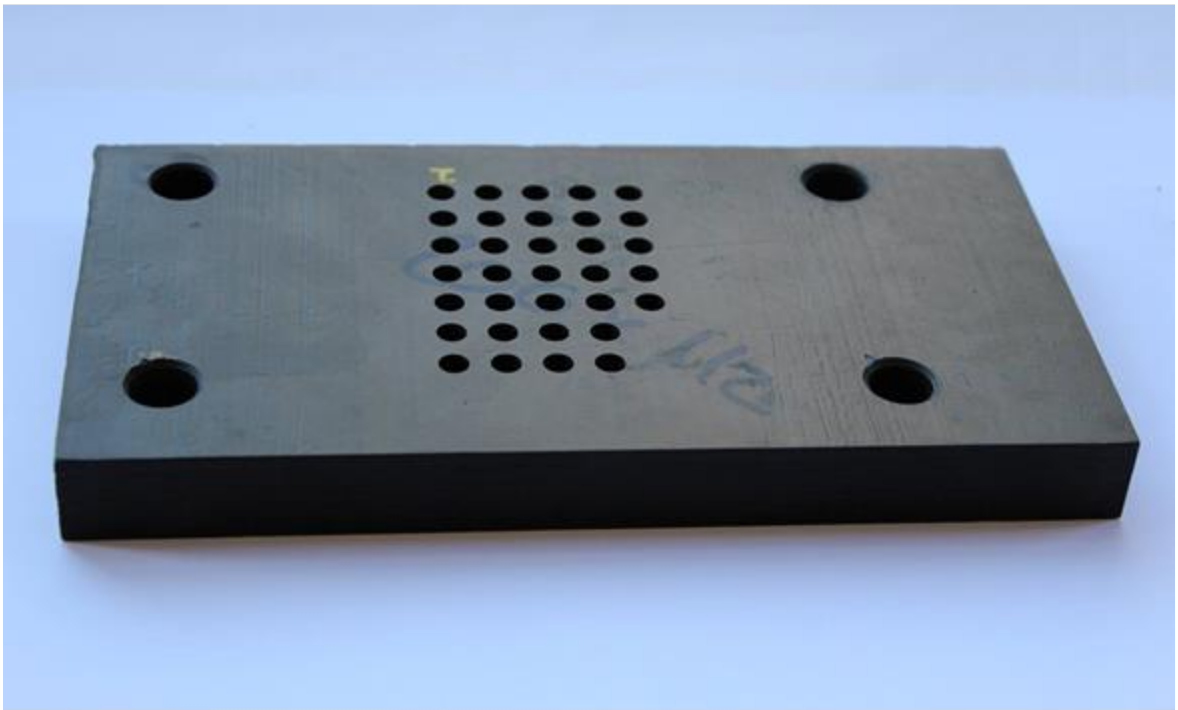


Figure 4. Carbon fibre laminate used in the study

In this first study, a total of 32 holes of 6 mm diameter were drilled using the same model of drill bit. However, 16 holes were drilled using a drill bit without coating and the other 16 using the same drill bit with a hardcut coating. The drill bits were purchased from Dormer Tools Ltd. Their specialised staff chose the more adequate tool for this study taking into account the material of the work-piece, its thickness, the type of machine used for the drilling, the diameter of the holes and also the price.

Figure 5. Dormer R123 6.0 solid carbide spotting drill uncoated

The selected drill bit was a Dormer R123 6.0 solid carbide spotting drill with 90 degree point, 17 mm flute length and a regular 29 degree rake angle. The catalogue specifications provided by Dormer Tools Ltd can be found in Appendix B. It is interesting to notice that this type of drill does not belong to any of the main types mentioned in the previous section. However, the company assured that it was the most appropriate model for the job due to its characteristics. The 90 degree point geometry gives a cleaner cut and better hole shape. Also, it reduces the amount of delamination around the hole edge when drilling layered materials.

The hardcut coating that used some of the drills was a Titanium Silicon Nitride coating. No further information about the carbide or the coating could be given by the company due to its policy.

Figure 6. Dormer R123 6.0 solid carbide spotting drill coated

The drilling process is characterised by what are known as drilling parameters. The two main parameters are the axial feed (f [mm/rev]) and the spindle speed (n [rpm]), which are also known as cutting parameters. From these two and knowing other characteristics as the drill diameter, other related parameters can be determined, such as the cutting velocity or the feed rate.

The spindle speed (n) is the most important factor influencing the cutting velocity (v_c [mm/min]). The cutting velocity varies along the radial direction during drilling. Ignoring the feed, its expression at the perimeter of the drill is –with D being the drill diameter – the following:

$$v_c = \pi \cdot D \cdot n \quad (1)$$

The axial feed (f) is the drill advancement per revolution along the drilling direction. The feed rate (f_r [mm/min]) is the speed at which the drill advances into the work-piece, and it is related to the feed (f) and the spindle speed (n) by:

$$f_r = f \cdot n \quad (2)$$

Therefore, the conditions for each test were selected varying the two main parameters of the drilling process: the axial feed (f) and the spindle speed (n). Four different levels –values taken by the parameters – were defined for each parameter as it is shown in Table 1. Wide ranges were used for the parameters' values in order to clarify their influence in the damage of the laminate. However, all values fit into other ranges used in previous studies.

Table 1. Drilling parameters' levels

Level	Parameters	
	Axial feed [mm/rev]	Spindle speed [rpm]
1	0,005	500
2	0,01	2000
3	0,03	4000
4	0,05	6000

Although 32 holes were drilled, only 16 different test conditions were carried out, as the same conditions were applied for both the uncoated and the coated drills. By analysing the holes of each drill that were performed under the same conditions, the effect of the coating could be assessed too.

As Table 2 shows, for the elaboration of the tests plan 16 different test conditions were defined corresponding to unique combinations of the drilling parameters' levels.

Table 2. Tests performed in the first study with both uncoated and coated drills

Test	Parameters (Levels)	
	Axial feed	Spindle speed
1	1	1
2	1	2
3	1	3
4	1	4
5	2	1
6	2	2
7	2	3
8	2	4
9	3	1
10	3	2
11	3	3
12	3	4
13	4	1
14	4	2
15	4	3
16	4	4

As it has been previously said, wear has a great impact on the thrust force and hence on delamination. To avoid this problem, two drill bits of each type were purchased. Thus, each single drill bit had to drill only 8 holes and wear could not develop enough to have influence on the results. The set of drills is shown in Figure 7. Uncoated 1 and Coated 1 would drill tests 1 to 8 and Uncoated 2 and Coated 2 tests 9 to 16.

Figure 7. Whole set of drills used in the study: two uncoated and two coated

Still, the drill bits were observed and analysed before and after this study in order to observe the wear produced during the drilling.

A prototype of the work-piece with the different holes – specifying their parameters and the drill used – was developed using the Solid Works design software. This document was sent to the university's workshop in order to set up the drilling operation. The prototype can be found in the Appendix B of the report.

For the drilling, a CNC Milling machine of the university was used. The machine was a Bridgeport VMC 600 with a maxim spindle speed of 8000 rpm. In order to introduce the different drilling parameters as well as the cutting conditions, a computer software called Feature CAM was used. This software converts a CAD file into a CNC package by a conversational code named NC Code. Using this software, each hole characteristics (location of the hole in the work-piece, feed rate, spindle speed, depth, etc.) were specified.

The depth of the drilling operation was set on 23 mm in order to ensure through hole drilling. The operation was performed without coolant. Also, a pecking drilling cycle was defined to ease chip evacuation. A peck was done per advanced millimetre, resulting in 23 pecks per hole.

After the drilling, the laminate's damage and the drills were assessed. As it has been previously said, the study included the observation and analysis of delamination as well as the effect of the coating in the drill bits. Although there was a desire to assess the surface roughness of the holes too, the university did not have the necessary equipment in order to do so.

Optical microscopy and digital image analysis were used to observe and analyse both the drills and the work-piece. All the equipment used was from the university. The optical microscope was a Nikon SMZ 800, while the computer software for digital image analysis was the NIS-Elements F 3.0. Almost all the images taken with the optical microscope had a magnification of x10.

In order to measure delamination, the delamination factor F_d was used. It was obtained from the ratio of the maximum diameter of the damaged region to the nominal hole diameter, as given in Eq. (3).

$$F_d = \frac{D_{MAX}}{D} \tag{3}$$

As previously mentioned, in order to assess the tool wear and the coating's impact, the drills were observed before and after the operation. Using the equipment previously described, images of the chisel edge, the cutting edge and the tip were taken in both situations.

4.0 Results and discussion (first study)

In this section the results of the first study are presented and discussed. The section has been structured in three different blocks regarding the three main regions that have been analysed: the holes entrance, the holes exit and the tools. The complete set of images taken with the optical microscopy of the holes can be found in Appendix B of the report.

Entrance of the holes

When analysing the top surface of the work-piece after the drilling, it was observed that the main damage in the holes entrance was not peel-up delamination, but the burning of the work-piece's surface. As it can be observed in Figure 8, in many of the holes, the surrounding area was damaged due to overheating. Damaged as it was the top surface after the drilling operation, this laminate would have been rejected in the industry.

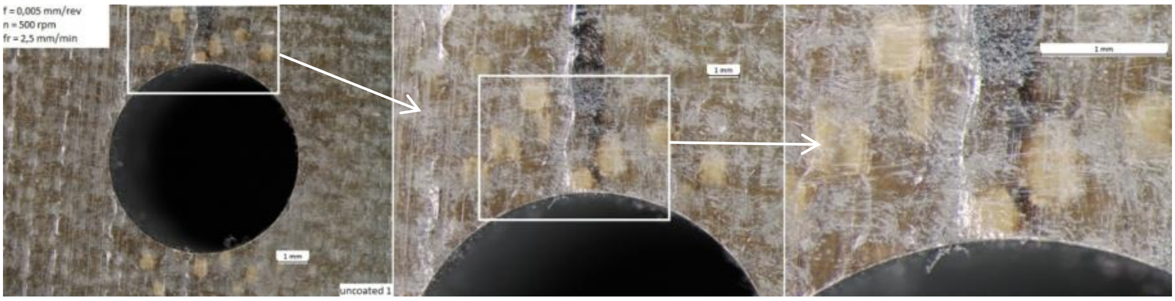


Figure 8. Burned surface surrounding the hole's entrance

The overheating was produced due to the excessive temperatures reached during drilling. Analysing all the holes showed that the damage was greater due to a lower feed rate, as the drill had more contact time with the work-piece. Also, as previously mentioned in the literature review, spindle speed influenced the heating too, since as the faster the spindle speed, the greater friction produced. In addition, it was observed that the last holes to be drilled with each drill were more likely to suffer the damage, as the drills did not cool fast enough and their temperature increased per hole.

But certainly, the main cause of the overheating was the drill's geometry. Although Dormer Tools Ltd specifically recommended the R123 spotting drill for the job, the results showed the opposite. Firstly, spotting drills are commonly used to spot drilling prior to the full drilling cycle with for instance a twist drill, in order to ensure accurate hole location and avoid drill deflection. Almost never they have been used to actually drill the hole.

The R123 model, although it was able to drill a 19 mm depth hole, its 17 mm length flutes were proved to be insufficient for an adequate chip clearance. Another characteristic that caused the temperature to rise dramatically was the absence of drill margins. Drill margins have different configurations, which are shown in Figure 9.

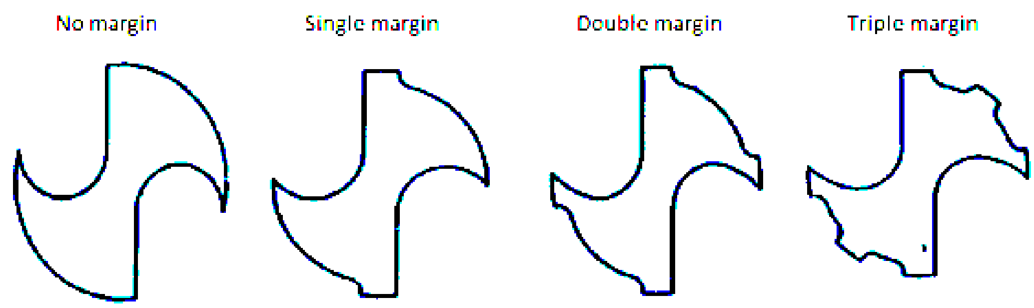


Figure 9. Different drill margin configurations

Most standard drilling tools are single margin, which means that they have one margin adjacent to the cutting edge in order to create the least amount of friction during the operation. Other less frequent options are the double or triple margin. The R123 has no margin, which means that the whole body of the drill is in contact with the work-piece during the machining, creating a lot of friction which inevitably causes the temperature to rise.

The use of coolant during the drilling operation could have avoided high working temperatures, improving the results obtained in this first study.

Apart from the burned area, there was also peel-up delamination in the contour of the entrance of the holes. It was assessed using the delamination factor F_d, which has been defined in the previous section of the report. The results for all the holes are presented down below in Table 3.

Table 3. Delamination factor F_d for peel-up delamination at the hole entrance

Test	F_d	
	Uncoated	Coated
1	1,03	1,04
2	1,06	1,14
3	1,19	1,22
4	1,17	1,17
5	1,17	1,17
6	1,21	1,21
7	1,21	1,22
8	1,23	1,23
9	1,01	1,04
10	1,04	1,09

11	1,04	1,14
12	1,06	1,06
13	1,08	1,12
14	1,06	1,12
15	1,09	1,09
16	1,06	1,12

In the first place, the results showed that the coating of the drills had no influence in peel-up delamination, as no improvement was observed regarding the holes drilled with the uncoated drills. Moreover, the holes drilled with the coated drills presented slightly worse results.

Regarding the influence of the drilling parameters in peel-up delamination, the analysis has shown that high feed rates over 60 mm/min minimise this type of defect. Table 4 presents the average values of F_d with feed rates under and above 60mm/min.

Table 4. Average peel-up delamination F_d values for under/above 60mm/min feed rates

	F_d	
	Uncoated	Coated
Feed rate < 60 mm/min	1,14	1,16
Feed rate > 60 mm/min	1,06	1,09

However, as it can be observed in Figure 10, assessing the results by spindle speeds showed that the F_d slightly increased with spindle speed.

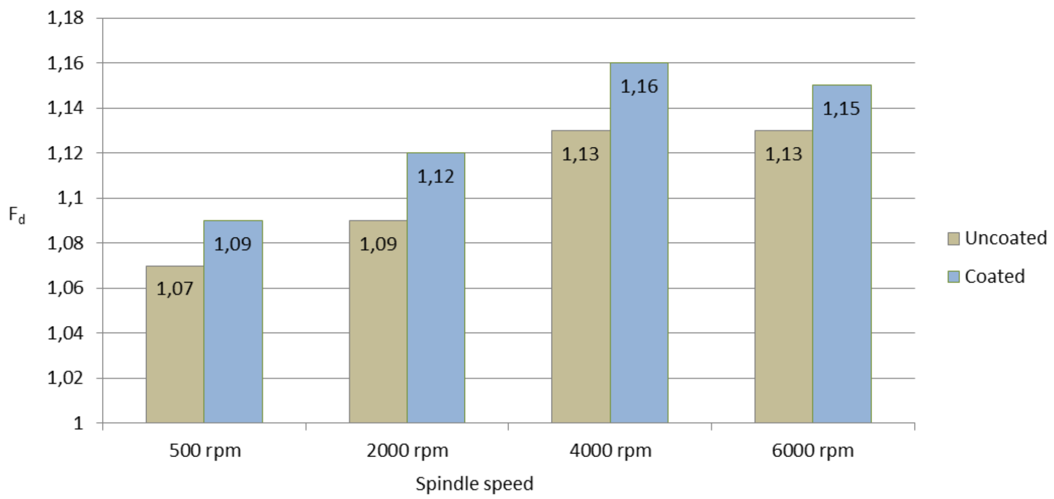


Figure 10. Graphic showing the average F_d for the different spindle speeds of the tests

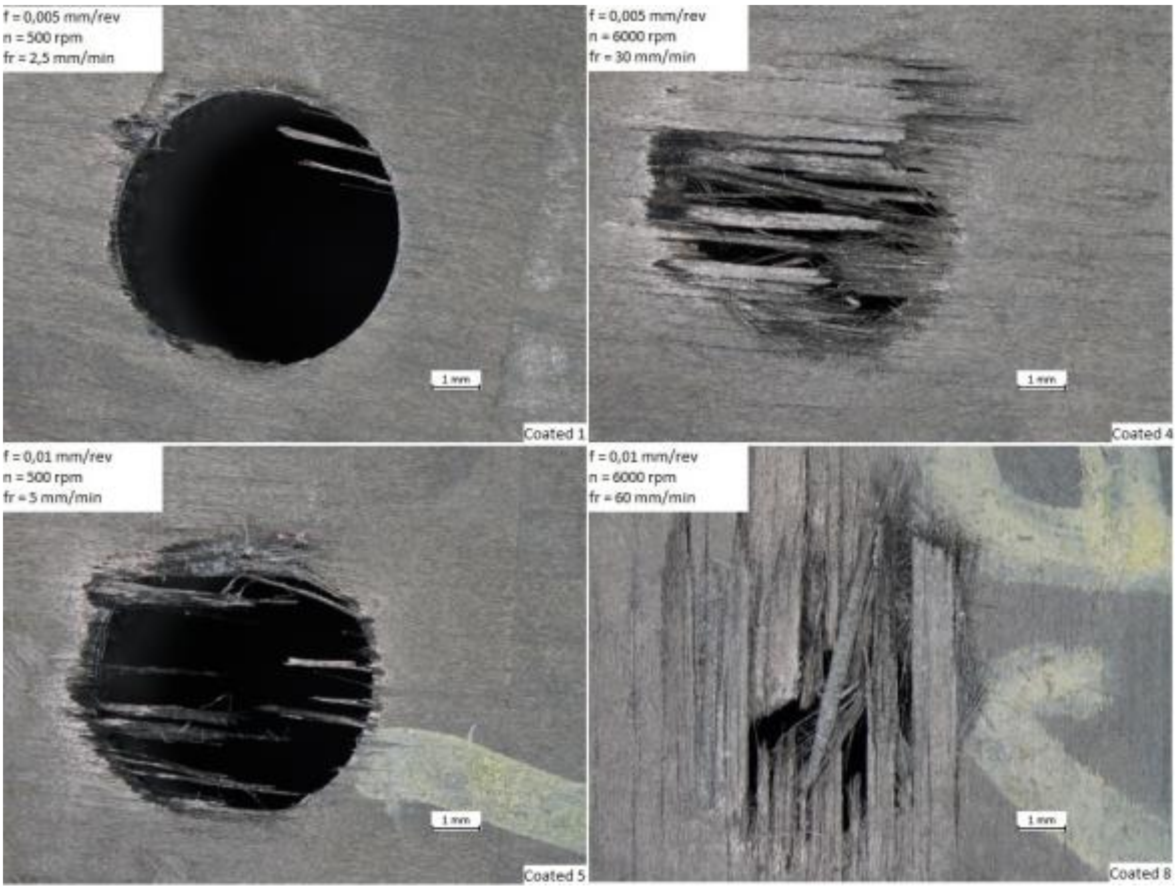
Combining both tendencies it can be concluded that a low feed rate with a high spindle speed present the worst results.

Exit of the holes

After observing the condition of the bottom surface of the laminate, there was no other choice than to give up calculating the push-out delamination factor F_d. Very poor results were obtained regarding hole quality due to great amount of push-out delamination that caused the presence of uncut fibres and fraying all over the exit hole. The large and unexpected amount of uncut fibres was caused mainly due to the drill's geometry and the high temperatures.

As analysed in the previous point, overheating was a problem in many of the tests. Observing the bottom surface of the laminate and the exit of the holes, it could be seen that it had influenced those results too. The holes that had greater burn marks surrounding the entrance of the hole, were in most cases the ones that had the poorest quality at the exit of the hole. Overheating can soften the matrix, making it more liable to be pushed by the drill avoiding to be cut.

Examining the exits of the holes, it was difficult to determine the effects of the drilling parameters in the results beyond their influence in the overheating, which has already been described above. However, as shows Figure 11, in general the holes drilled at 6000 rpm presented worse results than the ones drilled at 500 rpm, independently of the feed rate.



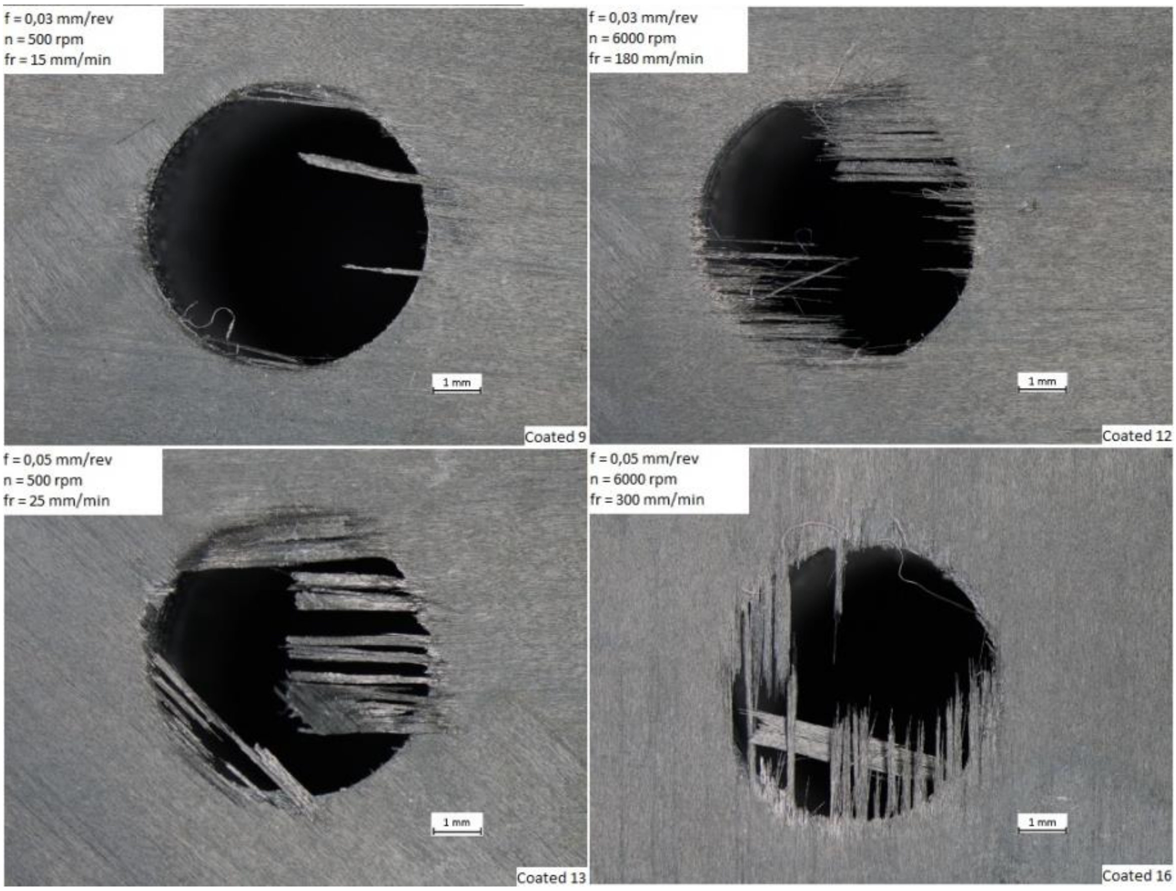


Figure 11. Comparison of the exits between the holes drilled at 500 rpm and 6000 rpm with the coated drills

The other main factor that caused the great amount of uncut fibre at the exits was the drill's geometry. The R123 spotting drill sharp point geometry with a 90 degree point angle, although it was supposed to reduce the occurrence of push-out delamination, it causes the areas closer to the perimeter of the hole to be cut later than the central areas, which can induce the pushing of the fibres. The coating did not affect the results, which were very similar for both the tests drilled with the uncoated and the coated drills.

Other point geometries could bring solutions to improve this problem. For instance, a brad point twist drill could be used. Its point geometry, which is shown in Figure 12, makes sure that the perimeter areas are cut almost at the same time as the central ones, which has already been proved that gives accurate sized holes.

Figure 12. Comparison between a spotting drill (a) and a brad twist drill (b) point geometries

Another improvement could be the use of a sacrifice board under the work-piece during the drilling operation. The board, made of a softer material like aluminium or wood, would ensure a softer exit transition from the work-piece, providing a cleaner and better quality hole exit.

Tools

As planned, the drills were observed and analysed using optical microscopy with digital image analysis before and after the drilling tests in order to detect wear and damage.

The observations showed that all of them suffered wear, although at different levels. Regarding the drills, the hardcut coating produced an effective result. In Figure 13, it can be seen how the cutting edges of the two coated drills presented less wear than their counterparts uncoated.

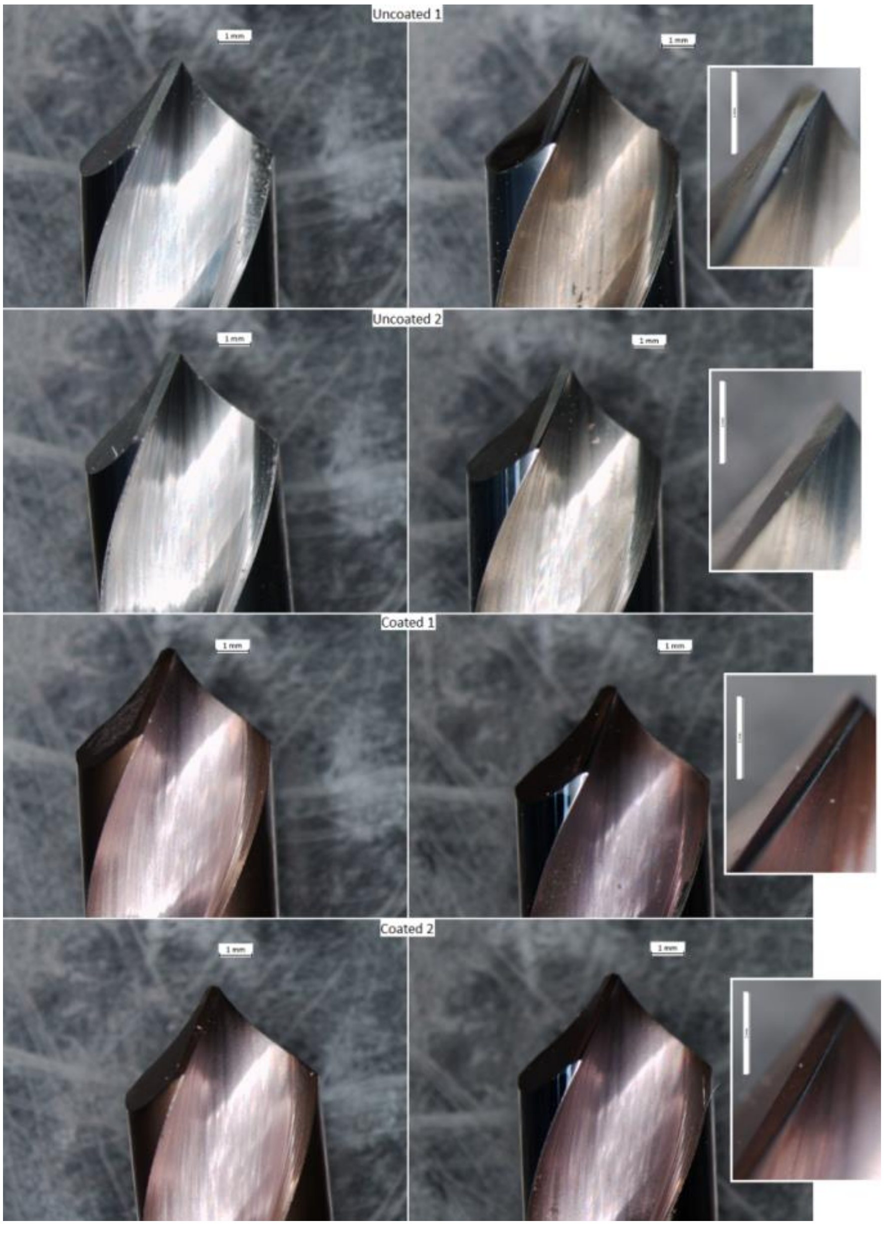


Figure 13. Images of the cutting edge before and after the drilling

Regarding the chisel edges of the drills, the objective was achieved. Four drills in total were purchased in order to avoid the influence of wear in the results and, although they showed signs of wear too (Figure 14), the damage was never enough to have had a great influence on push-out delamination.

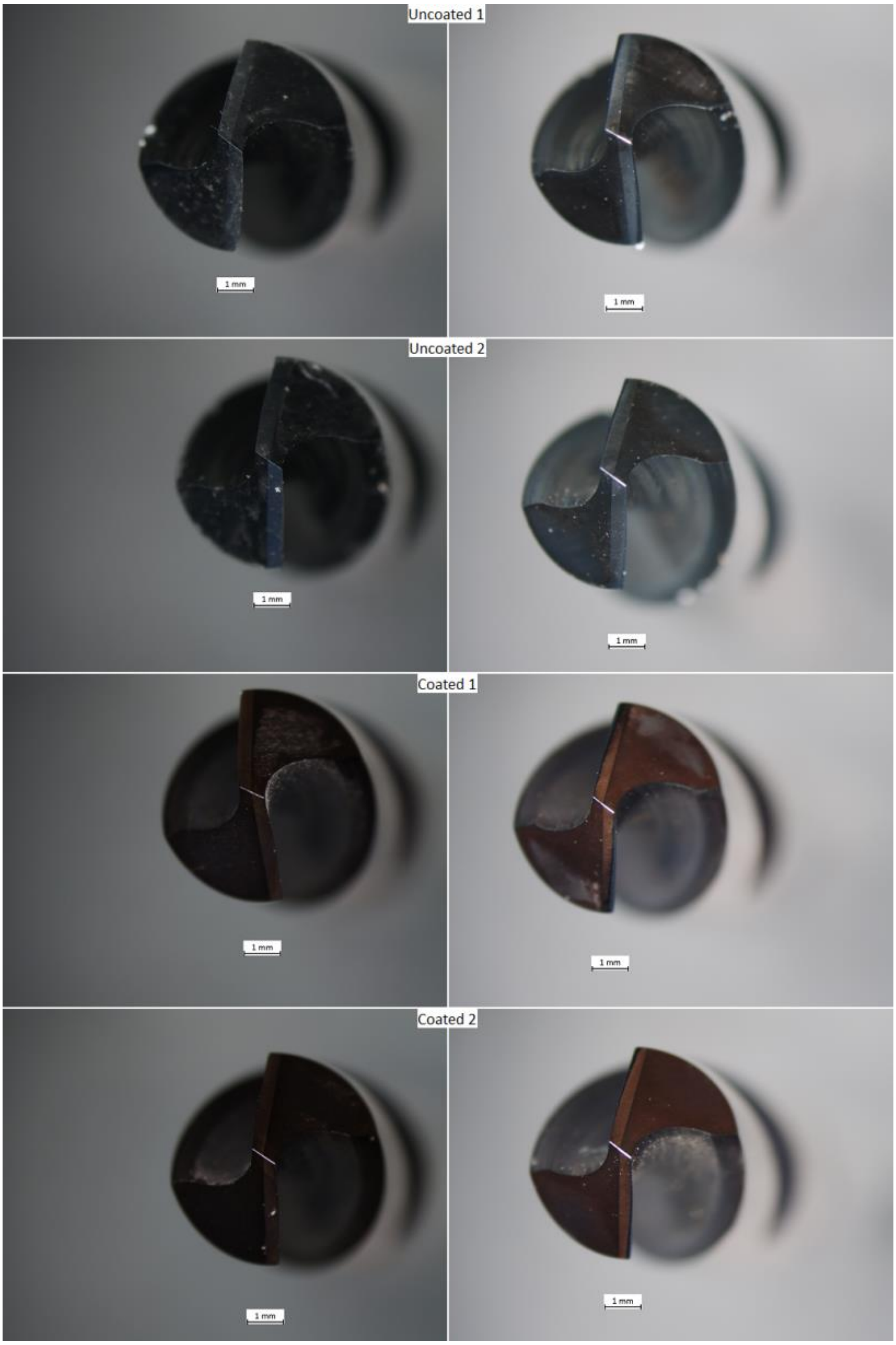


Figure 14. Images of the chisel edge before and after the drilling

Overheating during the operation has been pointed out as one of the main problems during the study. The drills suffered the high temperatures too, and burn marks were observed along the drill point. The heat caused the most damage to the drills as well as the top surface of the work-piece, when low feed rates and high spindle speeds were used, ergo when longer and more intense contact was produced. Therefore, the drills that drilled the first eight tests presented more burn marks than the ones that drilled the last eight. However, due to the coating in the coated drills the damage was less severe than in the uncoated (Figure 15).

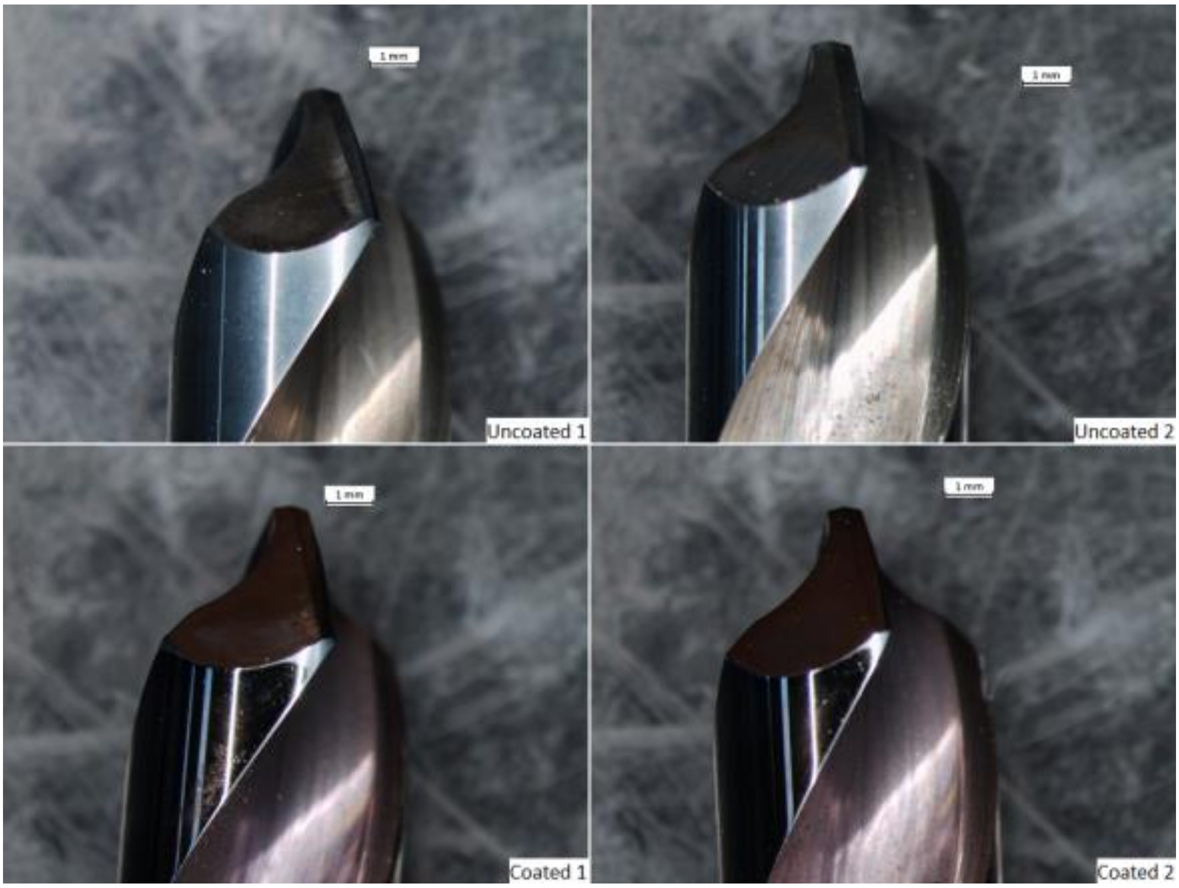


Figure 15. Burn marks along the drill points after the drilling

5.0 Experimental programme (second study)

After analysing the results presented on the previous section, a second study was carried out. The aim of this second study was to find improvements regarding the results obtained in the first study of the project, especially in the overheating and in the quality of the holes exits.

Therefore, using the parameters – axial feed and spindle speed – that got some of worst results in the first study, four new different tests were performed with different drilling conditions. These new conditions included the use of a sacrifice board and the use of coolant. The sacrifice board was a laminate of aluminium (Figure 16), while the coolant was a mixture of water and oil with a dilution ratio of 5%.

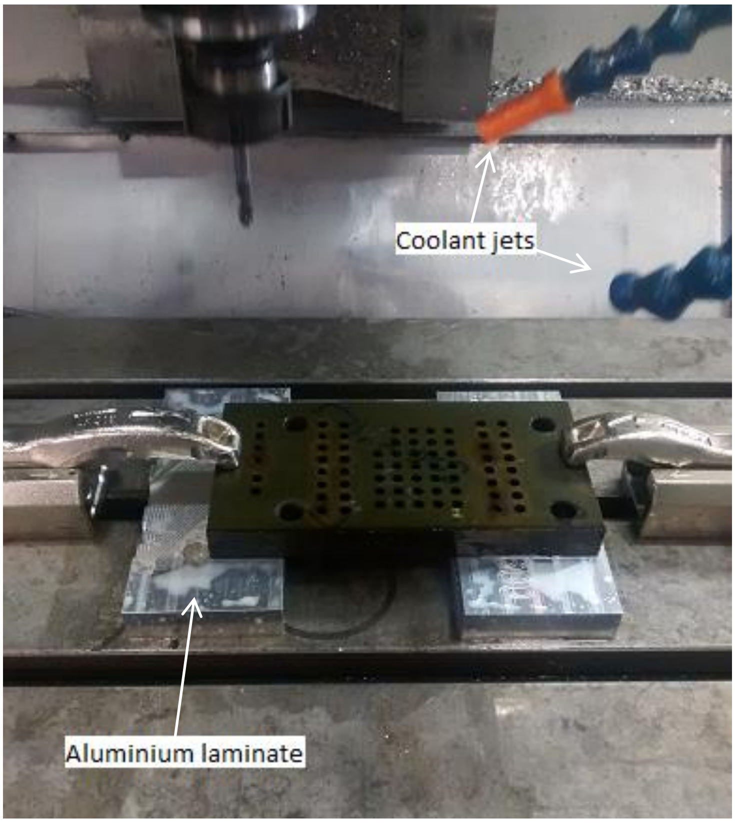


Figure 16. Set up for the drilling with the aluminium sacrifice board

The different tests are shown in Table 3. The parameters were the same as in test six of the first study, as the hole presented burn marks on the top surface and very poor quality at the hole's exit. The drill used for these tests was the one that was less worn from the first study, which was the coated drill that drilled the holes 9 to 16 (Coated 2), while the work-piece was the same as in the first study.

Table 3. Tests performed in the second study

	Axial feed = 0,01 mm/rev Spindle speed = 2000 rpm	
Test	Coolant	Sacrifice board
1	No	No
2	Yes	No
3	No	Yes
4	Yes	Yes

As it can be observed in Table 3, all the different combinations concerning the new drilling conditions were tested, which included even drilling without using any of the two added modifications, ergo drilling the hole in the same conditions as in the first study.

The drilling operations were performed using the same machine.

After the drilling, new observations and analyses were made using the optical microscope and the digital image analysis software. The top surface of the work-piece and the exit of the holes were the main targets of this study regarding the first results. In this second study, the drill was not analysed as the very different conditions of each hole's drilling operations made any type of conclusions very difficult to draw

6.0 Results and discussion (second study)

Down below, the results of the second study are presented. Figure 17 shows the observations of the entrances and exits of the holes for all four tests using optical microscopy.

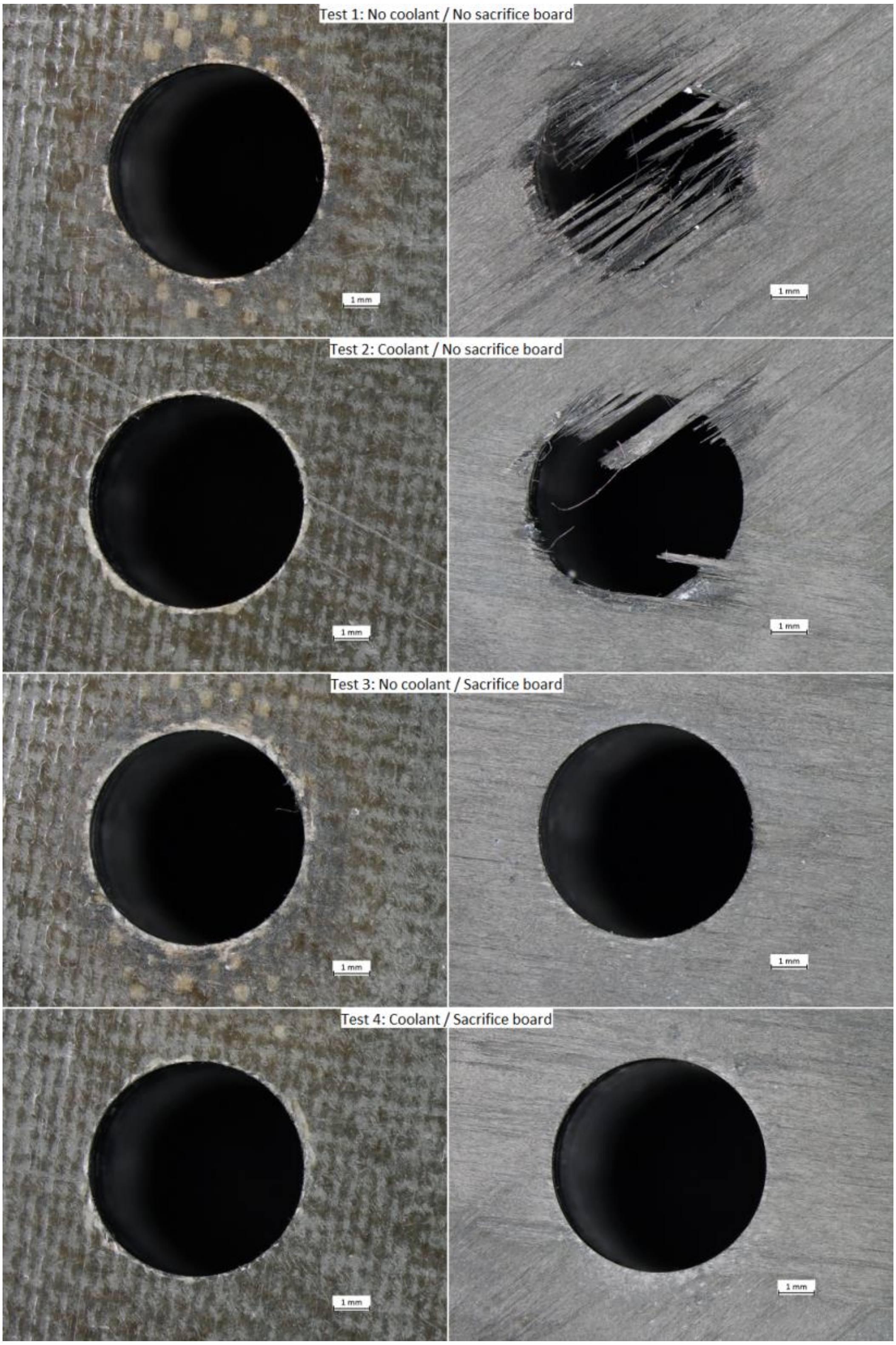


Figure 17. Images of the entrance (1st column) and the exit (2nd column) of the holes for the four tests in the 2nd study

Entrance of the holes

After analysing the results of the first study, in order to reduce the overheating that had caused the burn marks on the top surface of the work-piece, an improvement that was considered was the use of coolant during the drilling operation.

Observing the results of this second study in Figure 17, it was confirmed that using coolant the working temperatures did not reach the same high values and the damage was reduced. The entrance of the holes of tests one and three, which were drilled without coolant, showed the same burn marks that appeared in the first study. However, in tests two and four, coolant was used during the operation, therefore the surrounding areas of the entrances showed no sign of burn marks afterwards.

Exit of the holes

To improve the poor quality and the amount of uncut fibres at the holes exits in the first study, one of the solutions that were proposed was the use of a sacrifice board. Also, overheating was listed as one of the main causes.

Comparing the exit of the holes in tests one and two in Figure 17, it was noticed that the use of coolant reduced the amount of push-out delamination. This proved the influence of the heat on the presence of the uncut fibres, which was pointed out in the first study.

In addition, as it can also be observed in Figure 17, the use of a sacrifice board led to major improvements regarding the defects at the exit of the holes. In tests three and four, no presence of uncut fibres was detected. In both cases, the level of hole quality achieved allowed the calculation of the push-out delamination using the delamination factor F_d, which can be seen in Table 5.

Table 5. Delamination factor F_d for push-out delamination at the hole exit

Test	F_d
3	1,17
4	1,19

7.0 Conclusions

After completing the first study it was concluded that:

1. A spotting drill, despite being a recommendation from a renowned company of the sector, was not the most suitable option for the job. Other types of drills like twist, step or core carbide drills would most certainly have given a better performance. The R123 spotting drill geometry caused unexpected overheating during the drilling operation that in most of the tests ruined the top surface of the work-piece, leaving burn marks on the surrounding area of the entrances of the holes. In addition, together with the heat, the drill's sharp point geometry caused severe push-out delamination that left a great amount of uncut fibres at the exits of the holes.

2. The drilling parameters also played an important role in the overheating. The temperature increased as the feed rate was lowered, as the tool remained in contact with the work-piece longer. Moreover, higher spindle speeds increased friction which also raised the working temperatures.

3. The holes that were drilled last with each drill were more likely to suffer overheating as the drills did not cool fast enough between tests.

4. A solution to improve the overheating problem could be the use of coolant during drilling.

5. The measurements of peel-up delamination using the delamination factor F_d, unlike what was stated in the literature review, showed that high feed rates had the best results, with values around 1'06. On the other hand, the F_d increased with spindle speed. Therefore, the worst results were presented by the holes that were drilled at low feed rates and high spindle speeds, with values around 1'21. The coating of the drills did not influence on the results, as the tests performed with the uncoated and the coated drills had almost identical results, with the F_d values of the holes drilled with the coated drills being slightly higher.

6. The F_d for push-out delamination could not be calculated because of the amount of uncut fibre and the poor quality at the exit of the holes. The coating of the drills did not influence the results as both exits for holes drilled with the uncoated and the coated drills looked much the same.

7. The higher working temperature caused a greater amount of uncut fibre. Also, drilling at high spindle speeds showed the worst results.

8. Some solutions to improve the finish of the exits of the holes could be to use a sacrifice board during drilling and use other tool point geometries like the one that offers the brad twist drill.

9. The analysis of the drills showed that the coating was an effective solution against wear and heat, as the coated drills exhibited less damage than their uncoated counterparts. Also, low feed rates and high spindle speeds had caused the greatest damage. Therefore, the uncoated drill that drilled holes 1 to 8 was the most damaged, while the coated drill that drilled the holes 9 to 16 was the least.

After the second study, the conclusions from applying two of the measures previously proposed to improve the first study results were:

10. The use of coolant during the drilling avoided reaching such high temperatures during the machining and no burn marks appeared on the top surface of the work-piece.

11. The sacrifice board of aluminium that was used led to great improvements on quality at the exit of the holes. The clean exits without uncut fibres allowed calculating the delamination factor F_d for push-out delamination.

12. For future drilling operations, the use of coolant and a sacrifice board are highly recommended to achieve the highest hole quality.

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Appendix A Project Management

Project work plan

Table 6. Work plan of the project

Work Package	2-1 02 feb	2-2 09 feb	2-3 16 feb	2-4 23 feb	2-5 02 mar	2-6 09 mar	2-7 16 mar	2-8 23 mar	2-9 20 abr	2-10 27 abr	2-11 04 may	2-12 11 may	2-13 18 may	2-14 25 may	2-15 01 jun
1 Review of existing literature															
2 Define scope of modelling and tests															
3 Drilling prototype with Solid Works															
4 Get an offer from Dormer Tools Ltd for specialized carbide drills															
5 Submit purchase order for two R123 spotting carbide drills uncoated															
6 Complete drilling model and submit to workshop															
7 Submit purchase order for two R123 spotting carbide drills coated															
8 Conduct first experimental study and analyse results															
9 Conduct second experimental study and analyse results															
Milestone: Final report												◆			

The project work plan was influenced by the great delay on the delivery of the purchased drills for the project. Initially, the drilling in the workshop was wanted to be done before the Easter break, but it had to be deferred until the end of April.

Individual Project Meeting Record

Project Title	**Effect of drilling process on hole quality, delamination of CFC**		
Supervisor	Dr. Elaheh Ghassemieh	Student	**Hector Figols Lopez**
Date and time	13h30, 17/02/2015	Location	Supervisor's office

Review of actions from previous meeting

-

Discussion, decisions, assignments

First introduction to the project.

In order to deepen into the matter, there is the need to read and comprehend different publications related with the project's subject.

Agreed actions and completion dates

The following week will be spent learning and getting documented about the project's subject.

Date and time of next meeting		Location of next meeting	
Supervisor signature		Student signature	

Project Title	**Effect of drilling process on hole quality, delamination of CFC**		
Supervisor	Dr. Elaheh Ghassemieh	Student	**Hector Figols Lopez**
Date and time	13h30, 27/02/2015	Location	Supervisor’s office

<u>Review of actions from previous meeting</u>

-

<u>Discussion, decisions, assignments</u>

A prototype of the drilling process needs to be done with Solid Works and be sent to the Lab Technicians.

<u>Agreed actions and completion dates</u>

During the following week a preliminary prototype of the drilling process needs to be done.

Date and time of next meeting		Location of next meeting	
Supervisor signature		Student signature	

Project Title	**Effect of drilling process on hole quality, delamination of CFC**		
Supervisor	Dr. Elaheh Ghassemieh	Student	**Hector Figols Lopez**
Date and time	11h00, 06/03/2015	Location	Supervisor’s office

Review of actions from previous meeting

Review and revision of the preliminary prototype of the drilling process.

Discussion, decisions, assignments

Some modifications need to be done to the preliminary prototype.

New specialized drill bits need to be purchased in order to drill the carbon-fibre composite sample.

The Risk Assessment Form needs to be submitted in order to work in the Lab.

Agreed actions and completion dates

During the following week the final prototype of the drilling process needs to be done.

The Company Dormer Tools has to be contacted in order to get an offer of different specialized carbide drill bits for carbon-fibre composite as soon as possible.

Contact Dr. Richard Gault and Mr. Jonathan Stewart in order to proceed with the Risk Assessment Form.

Date and time of next meeting		Location of next meeting	
Supervisor signature		Student signature	

Project Title	**Effect of drilling process on hole quality, delamination of CFC**		
Supervisor	Dr. Elaheh Ghassemieh	Student	**Hector Figols Lopez**
Date and time	11h00, 10/03/2015	Location	Supervisor’s office

Review of actions from previous meeting

Company Dormer Tools already contacted.

Discussion, decisions, assignments

Dormer Tools asks for specific information about the carbon fibre work-piece. Dr. Ghassemieh gives me the information in order to proceed.

Agreed actions and completion dates

Get the offer from Dormer Tools for the carbide drills.

Date and time of next meeting		Location of next meeting	
Supervisor signature		Student signature	

Project Title	**Effect of drilling process on hole quality, delamination of CFC**		
Supervisor	Dr. Elaheh Ghassemieh	Student	**Hector Figols Lopez**
Date and time	11h00, 13/03/2015	Location	Supervisor's office

Review of actions from previous meeting

Approval of the final prototype of the drilling process.

The drill bit offered by Dormer Tools is suitable.

Risk Assessment Form submitted correctly.

Discussion, decisions, assignments

Send the prototype of the drilling process to Dr. Richard Gault.

As the drill bit offer is approved, the drill bits need to be purchased.

In addition, Dormer Tool has to be contacted again in order to ask for a more specialized drill bit than the one offered in the first place.

Agreed actions and completion dates

As soon as possible:

Send the prototype of the drilling process to Dr. Richard Gault.

Contact Dr. Richard Gault in order to proceed with the purchase of the drill bits. Get access to the online platform to order the petition.

Get another offer from Dormer Tools.

Date and time of next meeting		Location of next meeting	
Supervisor signature		Student signature	

Project Title	**Effect of drilling process on hole quality, delamination of CFC**		
Supervisor	Dr. Elaheh Ghassemieh	Student	**Hector Figols Lopez**
Date and time	11h00, 19/03/2015	Location	Via email

<u>Review of actions from previous meeting</u>

Drilling prototype already sent to Dr. Richard Gault.

First purchase order created, approved and signed.

Second purchase offer from Dormer Tools needs revision as the price does not seem correct.

<u>Discussion, decisions, assignments</u>

Insist Dormer Tools to get the correct offer for the second purchase order.

While the drills are not delivered at the university start writing the report..

<u>Agreed actions and completion dates</u>

Order the second set of drills as soon as possible once Dormer Tools sends the correct offer.

Meet again once the drills have been delivered.

Date and time of next meeting		Location of next meeting	
Supervisor signature		Student signature	

Project Title	**Effect of drilling process on hole quality, delamination of CFC**		
Supervisor	Dr. Elaheh Ghassemieh	Student	**Hector Figols Lopez**
Date and time	11h00, 17/04/2015	Location	Supervisor’s office

<u>Review of actions from previous meeting</u>

The development of the report is already in process.

<u>Discussion, decisions, assignments</u>

One month after ordering the drills, they have not been delivered at the university yet.

Mistakes by the company Dormer Tools are delaying the delivery.

<u>Agreed actions and completion dates</u>

Take action in order to unblock the situation and get the drills the soon as possible.

Date and time of next meeting		Location of next meeting	
Supervisor signature		Student signature	

Project Title	**Effect of drilling process on hole quality, delamination of CFC**		
Supervisor	Dr. Elaheh Ghassemieh	Student	**Hector Figols Lopez**
Date and time	11h00, 24/04/2015	Location	Supervisor's office

Review of actions from previous meeting

The drills must be delivered at the university during this day.

Discussion, decisions, assignments

Book session at the workshop for the drilling.

Book time for using the optical microscope and the digital image analysis.

Agreed actions and completion dates

Do the drilling and the observations and analysis the soon as possible.

Date and time of next meeting		Location of next meeting	
Supervisor signature		Student signature	

Project Title	**Effect of drilling process on hole quality, delamination of CFC**		
Supervisor	Dr. Elaheh Ghassemieh	Student	**Hector Figols Lopez**
Date and time	11h00, 01/05/2015	Location	Supervisor's office

Review of actions from previous meeting

The drilling has been done.

Discussion, decisions, assignments

Unexpected results with burnings on the top surface and a lot of delamination and uncut fibre on the bottom surface.

Analyse the possible causes and find solutions at the problems.

Agreed actions and completion dates

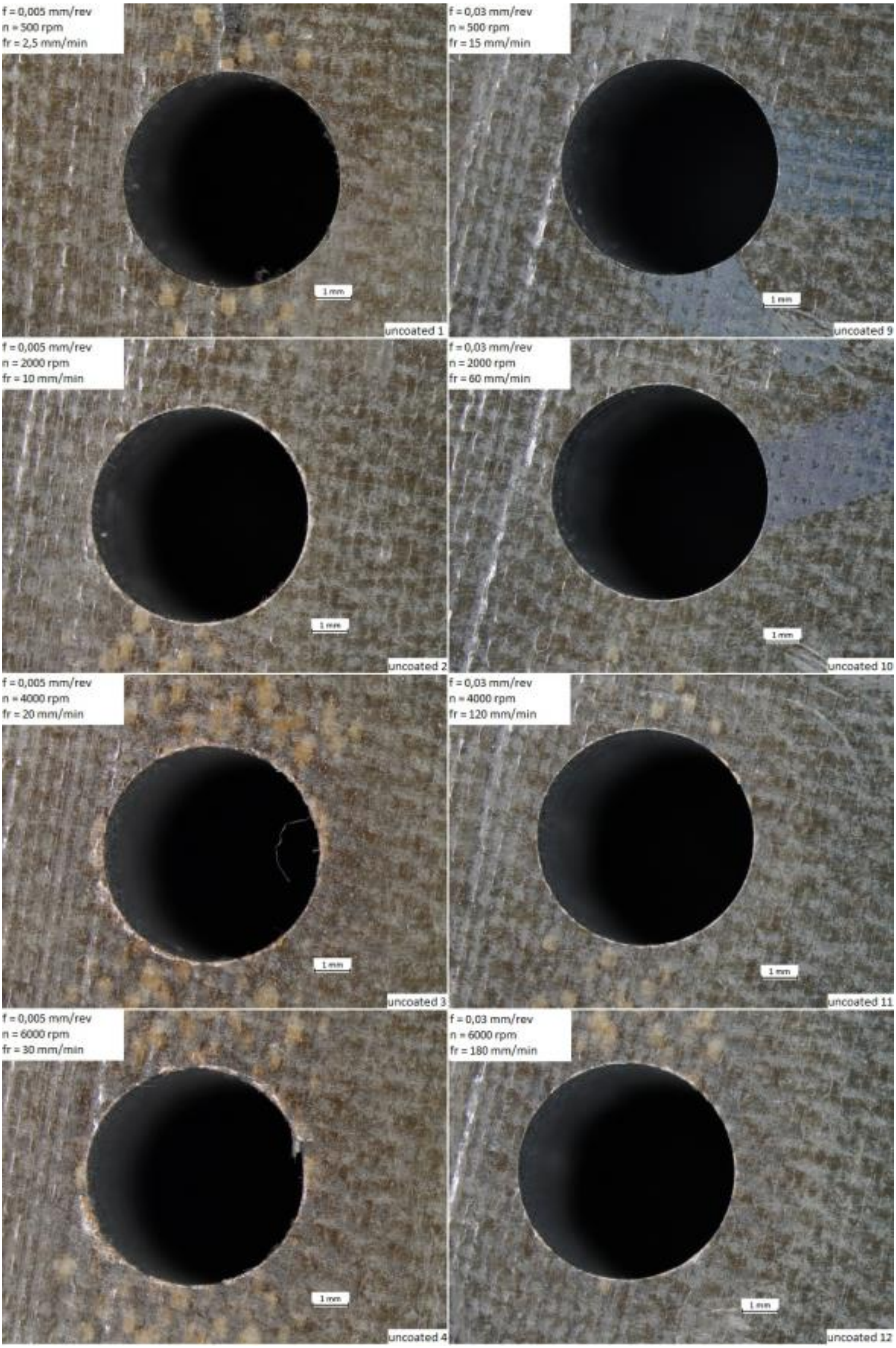
Continue with the analysis of the results.

Date and time of next meeting		Location of next meeting	
Supervisor signature		Student signature	

Appendix B

- Optical microscope images of the entrance and exit of the holes
- Drilling prototype
- Specifications for R123 spotting drill from Dormer Tools Ltd catalogue

Entrance of the holes



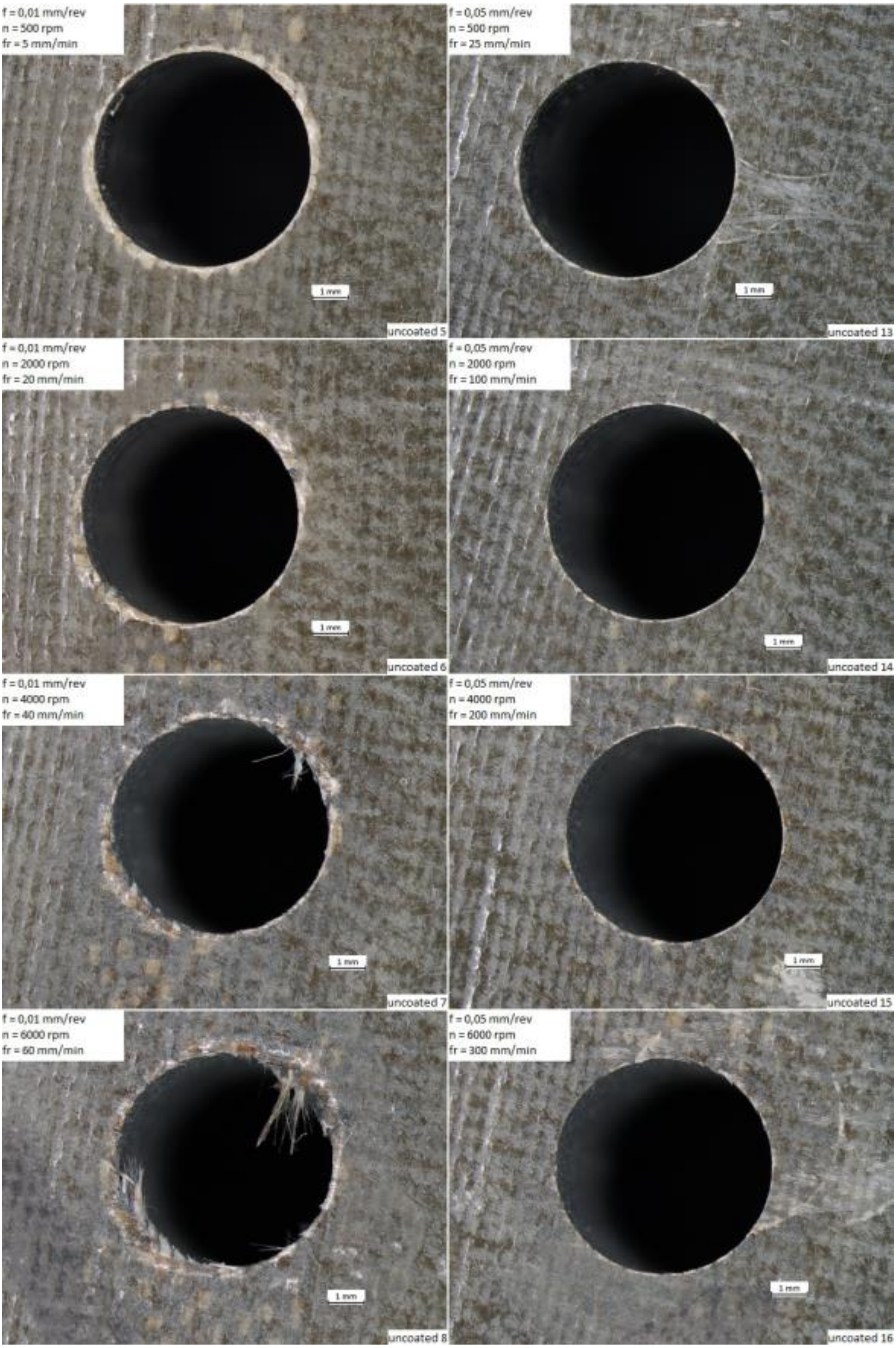
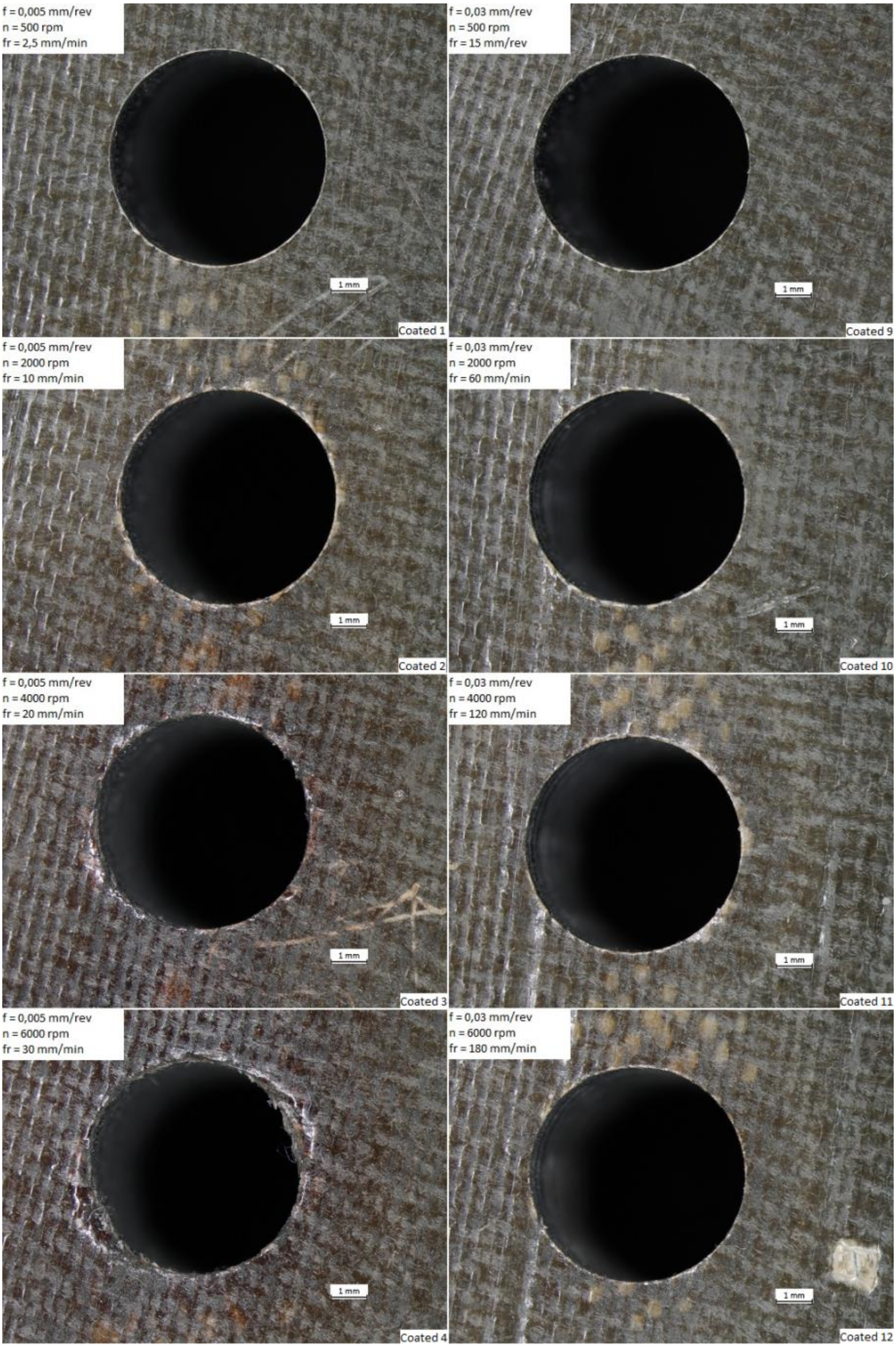


Figure 18. Optical microscope images of hole entrances of the uncoated drills tests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n = 500 rpm
fr = 2,5 mm/min
1 mm
Coated 1
f = 0,03 mm/rev
n = 500 rpm
fr = 15 mm/rev
1 mm
Coated 9
f = 0,005 mm/rev
n = 2000 rpm
fr = 10 mm/min
1 mm
Coated 2
f = 0,03 mm/rev
n = 2000 rpm
fr = 60 mm/min
1 mm
Coated 10
f = 0,005 mm/rev
n = 4000 rpm
fr = 20 mm/min
1 mm
Coated 3
f = 0,03 mm/rev
n = 4000 rpm
fr = 120 mm/min
1 mm
Coated 11
f = 0,005 mm/rev
n = 6000 rpm
fr = 30 mm/min
1 mm
Coated 4
f = 0,03 mm/rev
n = 6000 rpm
fr = 180 mm/min
1 mm
Coated 12

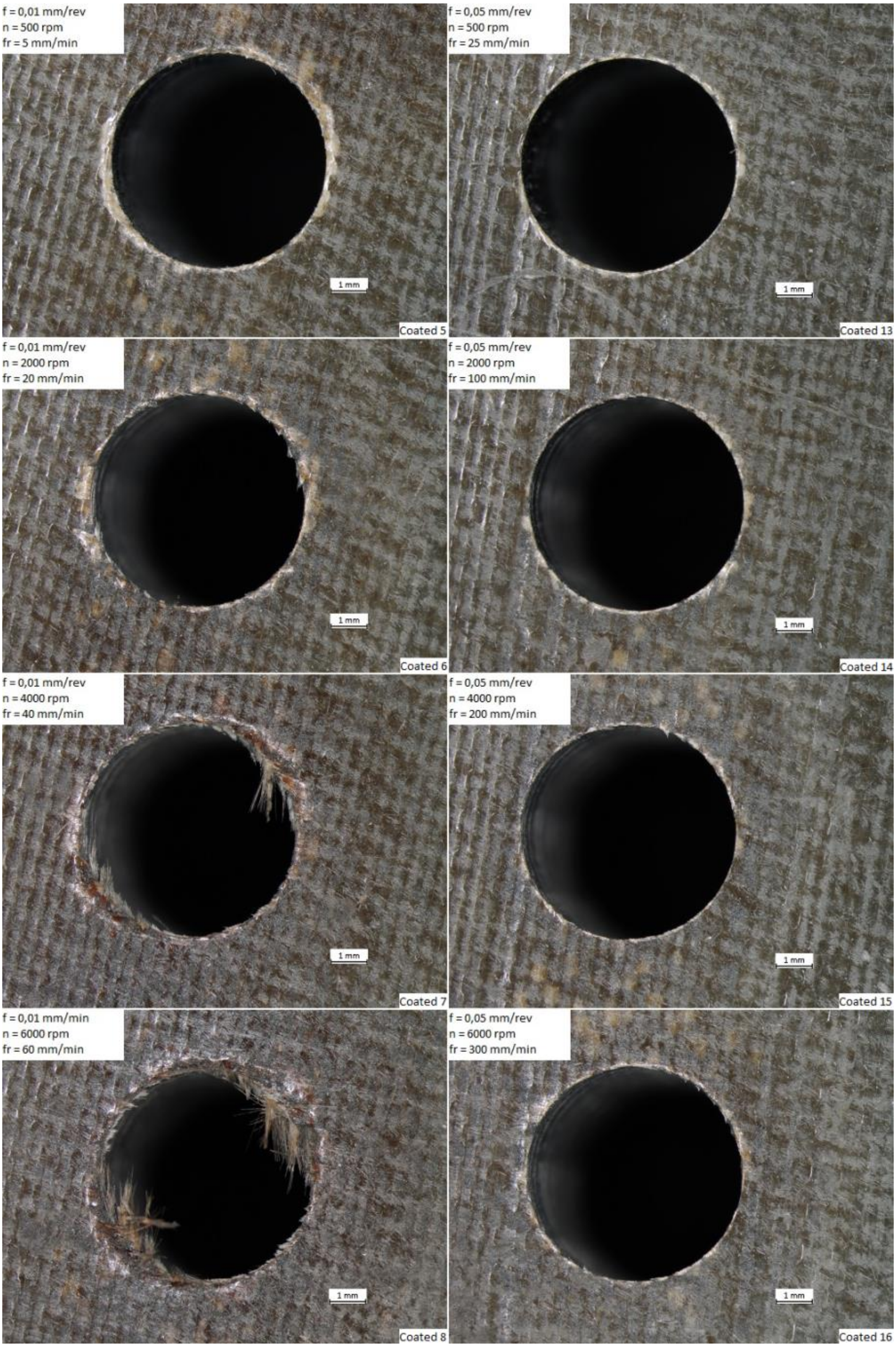
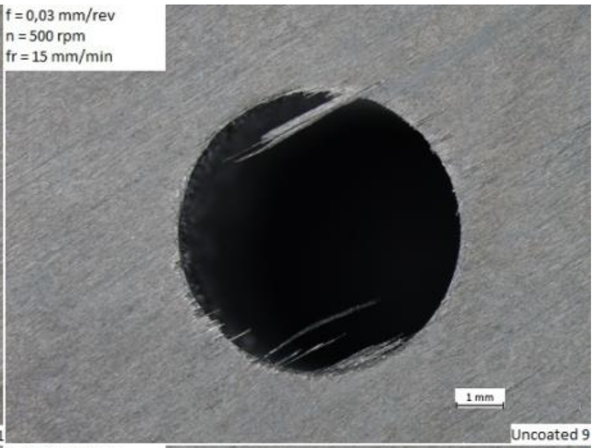
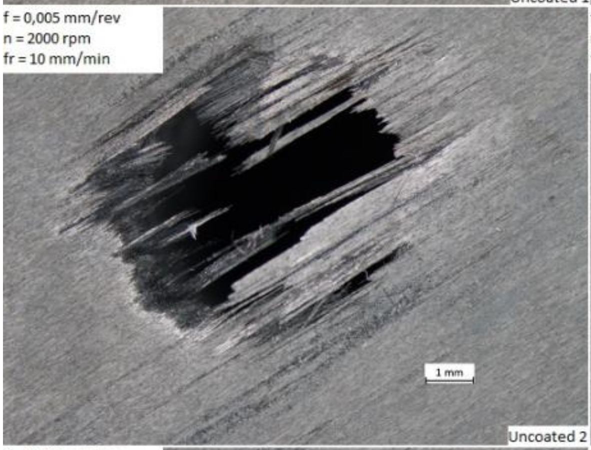
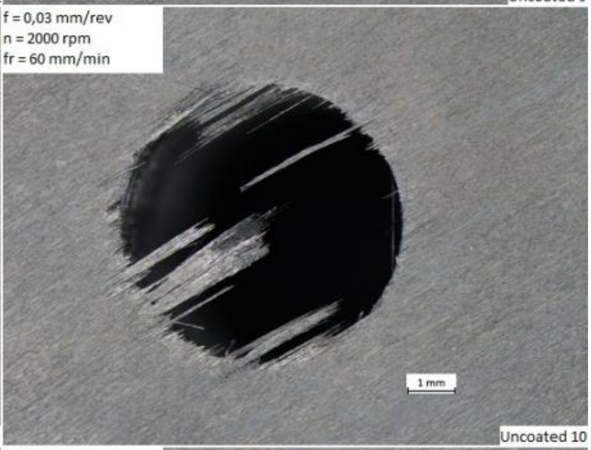


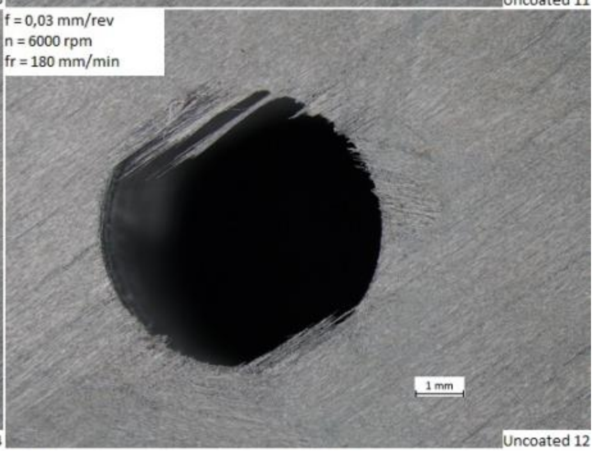
Figure 19. Optical microscope images of hole entrances of the coated drills tests

Exit of the holes









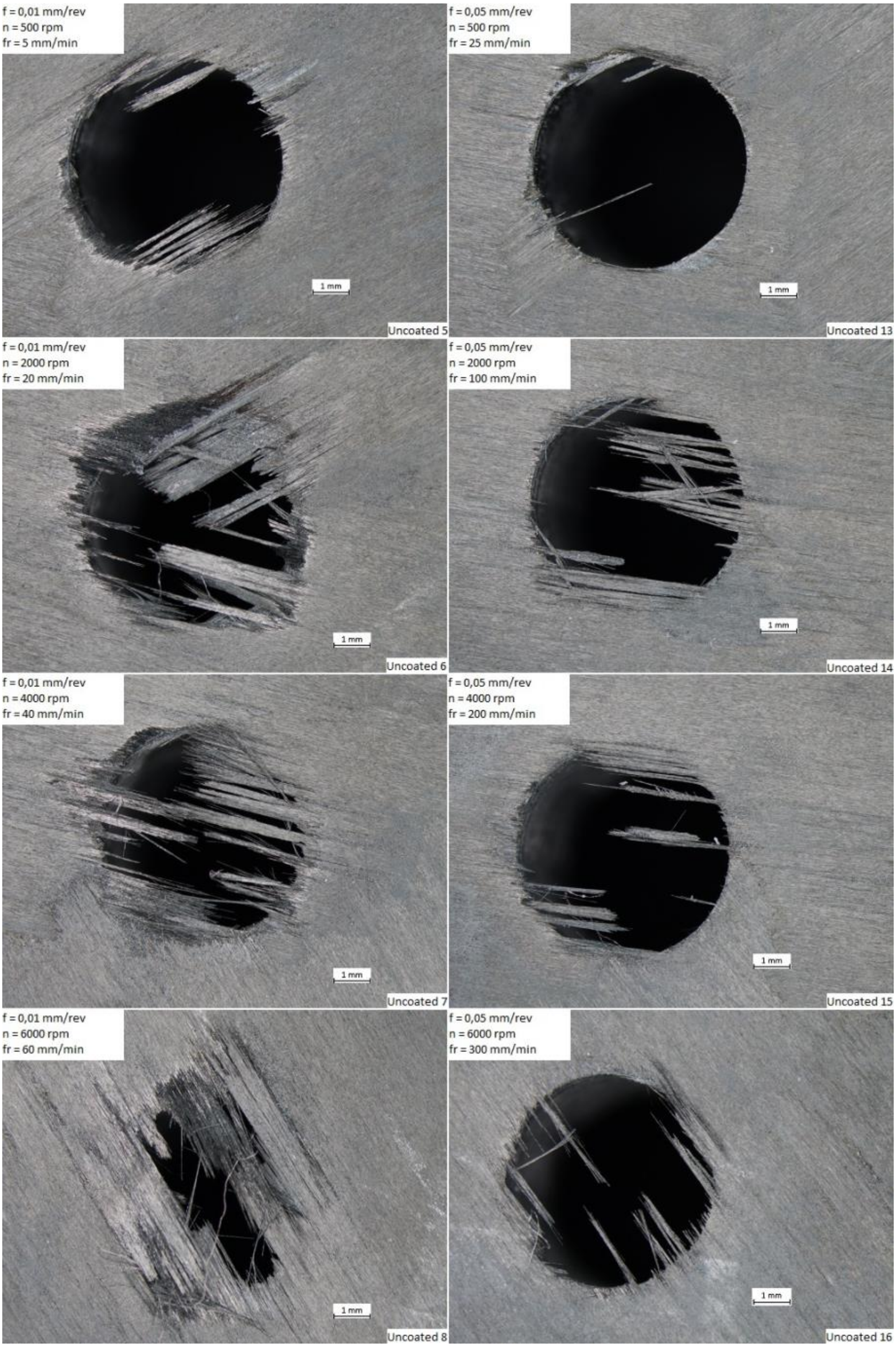
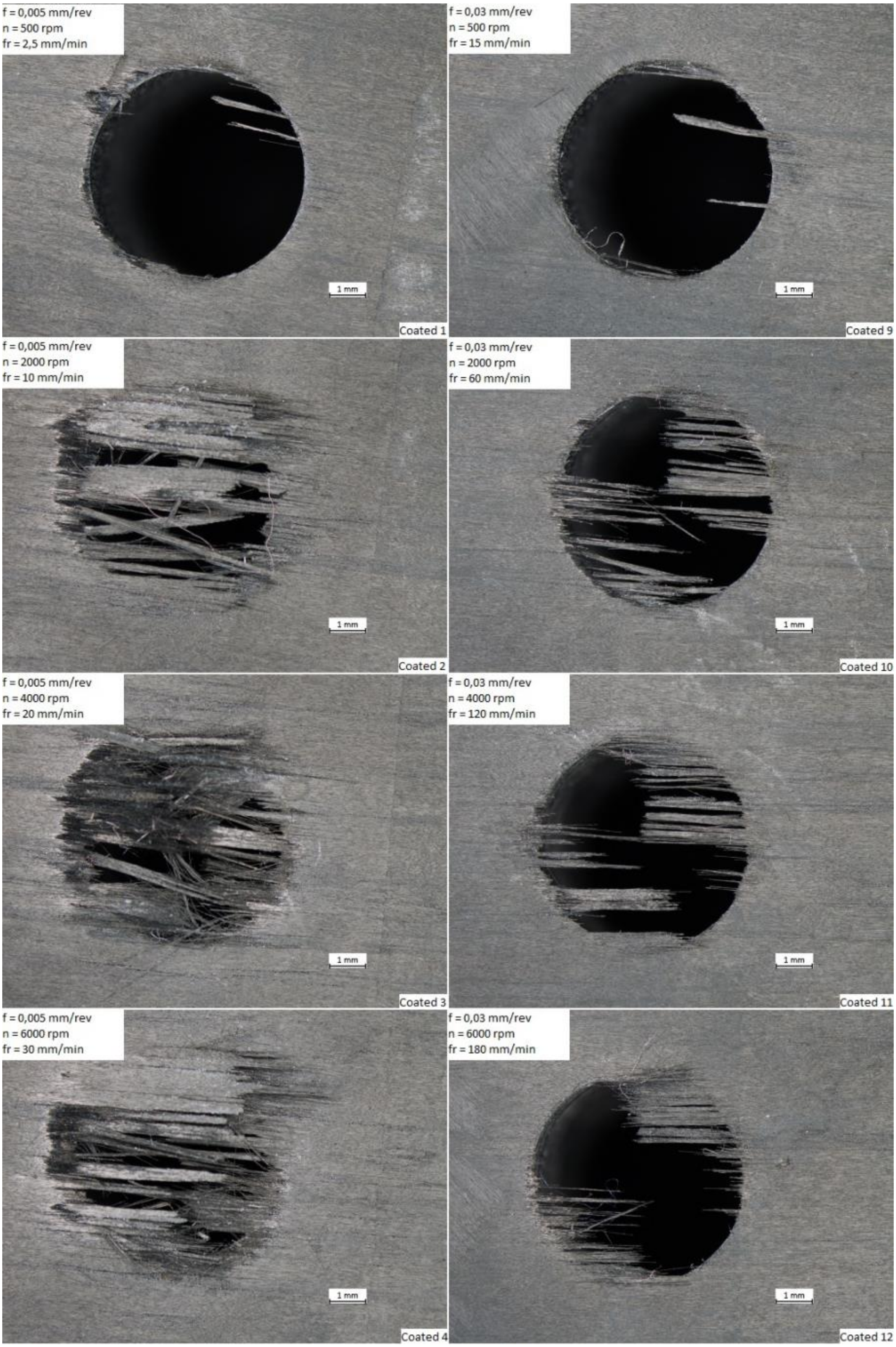


Figure 20. Optical microscope images of hole exits of the uncoated drills tests


f = 0,005 mm/rev
n = 500 rpm
fr = 2,5 mm/min
1 mm
Coated 1
f = 0,03 mm/rev
n = 500 rpm
fr = 15 mm/min
1 mm
Coated 9
f = 0,005 mm/rev
n = 2000 rpm
fr = 10 mm/min
1 mm
Coated 2
f = 0,03 mm/rev
n = 2000 rpm
fr = 60 mm/min
1 mm
Coated 10
f = 0,005 mm/rev
n = 4000 rpm
fr = 20 mm/min
1 mm
Coated 3
f = 0,03 mm/rev
n = 4000 rpm
fr = 120 mm/min
1 mm
Coated 11
f = 0,005 mm/rev
n = 6000 rpm
fr = 30 mm/min
1 mm
Coated 4
f = 0,03 mm/rev
n = 6000 rpm
fr = 180 mm/min
1 mm
Coated 12

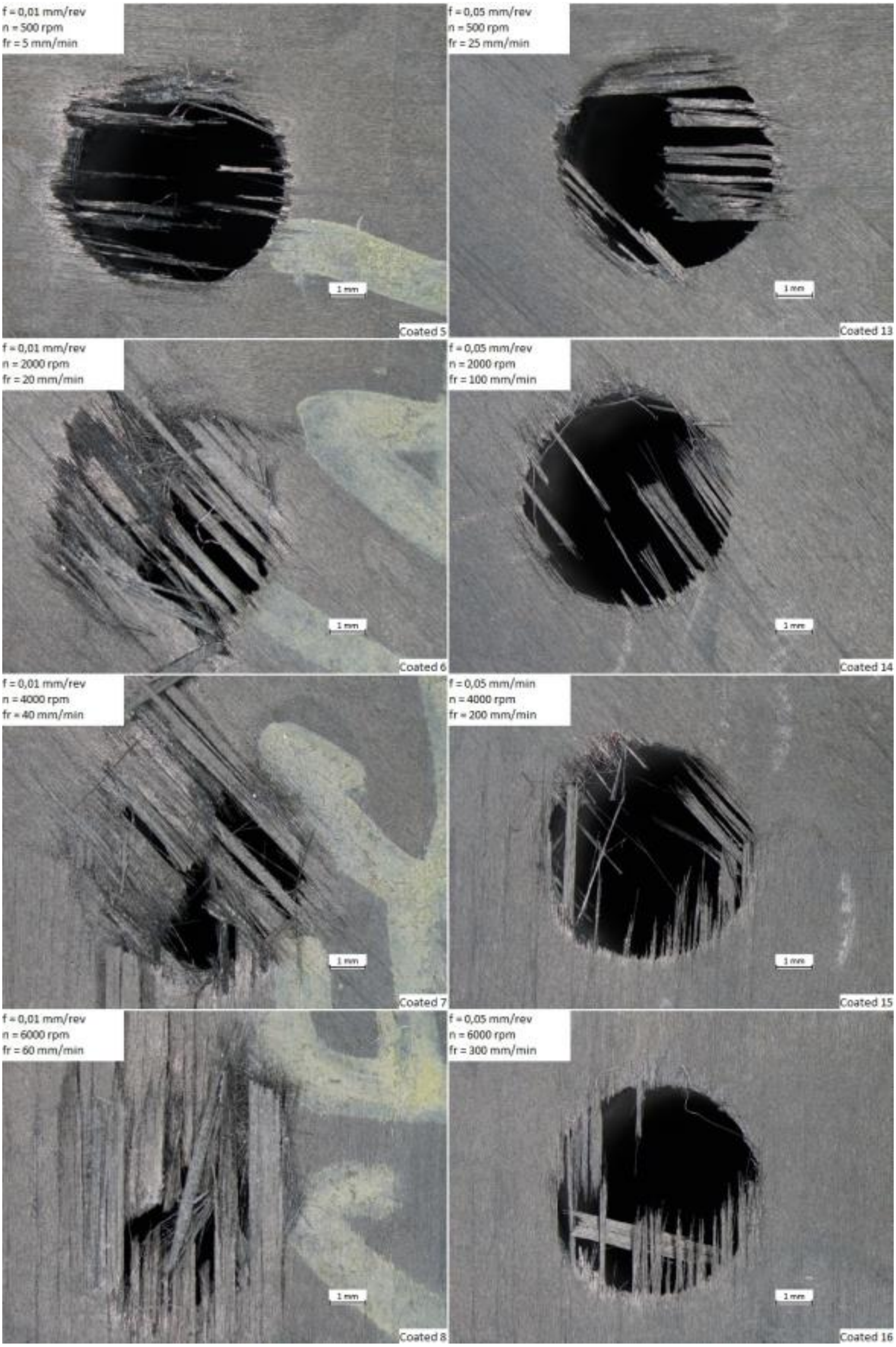
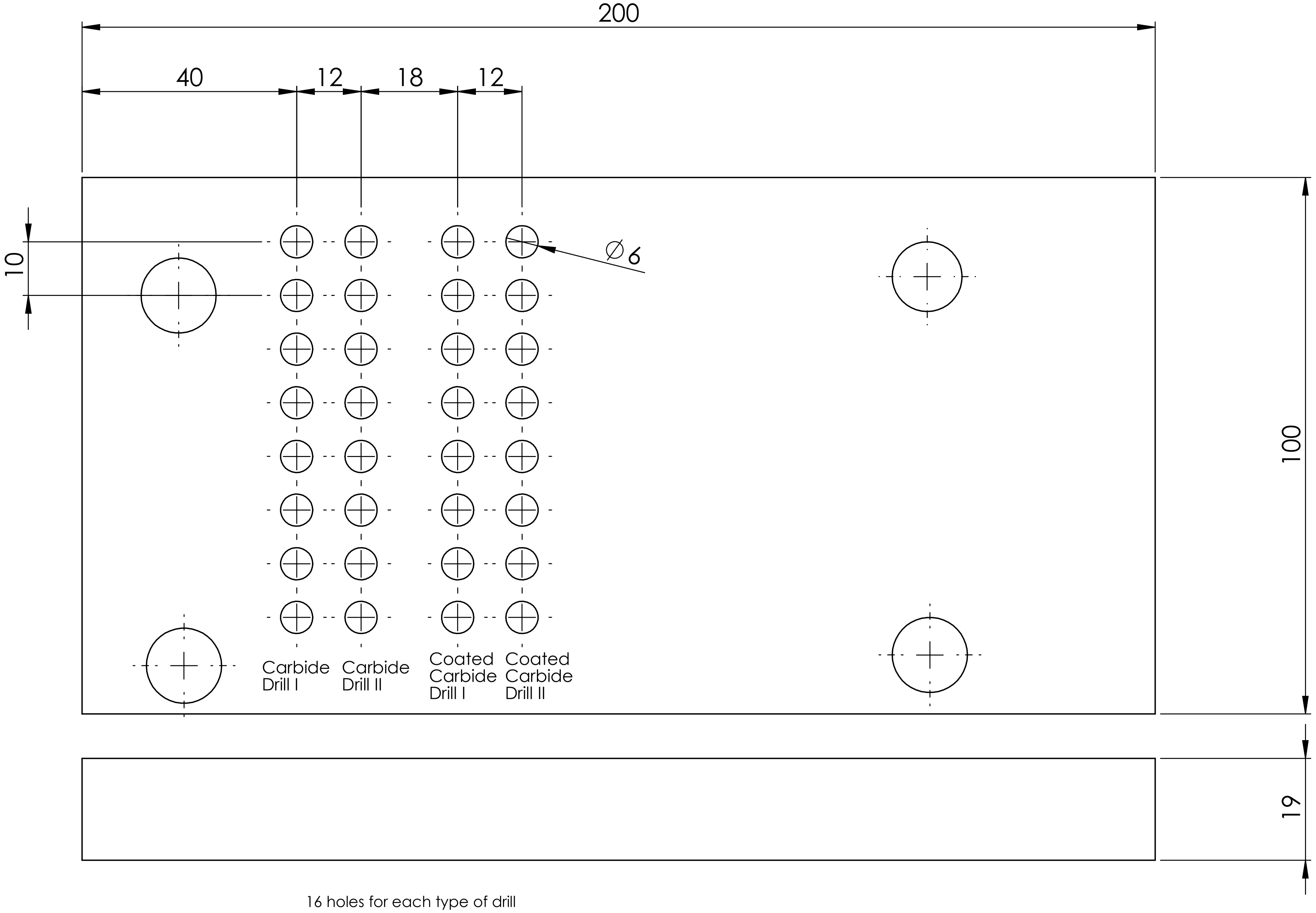


Figure 21. Optical microscope images of hole exits of the coated drills tests

Mesure:

- Thrust Force
- Delamination
- Surface Roughness
- Tool wear



16 holes for each type of drill

1 Spindle Speed = 500 rpm Feed Rate = 2,5 mm/min	9 Spindle Speed = 500 rpm Feed Rate = 15 mm/min
2 Spindle Speed = 2000 rpm Feed Rate = 10 mm/min	10 Spindle Speed = 2000 rpm Feed Rate = 60 mm/min
3 Spindle Speed = 4000 rpm Feed Rate = 20 mm/min	11 Spindle Speed = 4000 rpm Feed Rate = 120 mm/min
4 Spindle Speed = 6000 rpm Feed Rate = 30 mm/min	12 Spindle Speed = 6000 rpm Feed Rate = 180 mm/min
5 Spindle Speed = 500 rpm Feed Rate = 5 mm/min	13 Spindle Speed = 500 rpm Feed Rate = 25 mm/min
6 Spindle Speed = 2000 rpm Feed Rate = 20 mm/min	14 Spindle Speed = 2000 rpm Feed Rate = 100 mm/min
7 Spindle Speed = 4000 rpm Feed Rate = 40 mm/min	15 Spindle Speed = 4000 rpm Feed Rate = 200 mm/min
8 Spindle Speed = 6000 rpm Feed Rate = 60 mm/min	16 Spindle Speed = 6000 rpm Feed Rate = 300 mm/min

SolidWorks Student Edition.
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	NAME	DATE	DRAWN TO BS 8888
DRAWN	Hector Figols Lopez	13/03/2015	GENERAL TOLERANCES ISO 2768-m
CHECKED			
APPROVED			THIRD ANGLE PROJECTION
MATERIAL	Carbon Fibre Composite		

Effect of drilling process parameters on hole quality of aerospace CFRP parts

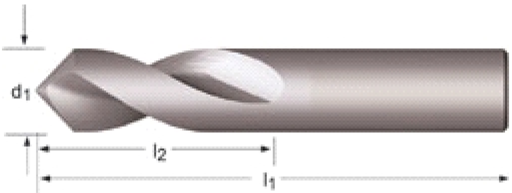
School of Mechanical & Aerospace Engineering
Queen's University Belfast

SHEET NO.	PROJECT	SCALE
1 OF 1	MEE1760	1:1
DRG. NO.		REV.
1		00

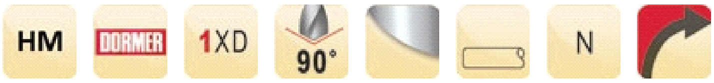
A3

R123

Short Spotting Drill - 90°



Four Facet Point upto 10,0mm



■ 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 2.1 2.2 3.1 3.2 3.3 3.4 4.1 4.2 4.3 5.1 5.2 5.3 6.1 6.2 6.3 6.4 7.1 7.2 7.3 7.4 8.1 8.2

d_1 Øh6 mm	d_1 decimal Inch	l_2 mm	l_1 mm	e-code	GBP
5.00	0.1969	16	62	R1235.0	37,05
6.00	0.2362	17	66	R1236.0	37,85
8.00	0.3150	22	79	R1238.0	51,70
10.00	0.3937	26	89	R12310.0	76,50
12.00	0.4724	30	102	R12312.0	106,00
16.00	0.6299	34	115	R12316.0	193,00
20.00	0.7874	40	131	R12320.0	283,00

Originality Report Summary (Turn-It-In)

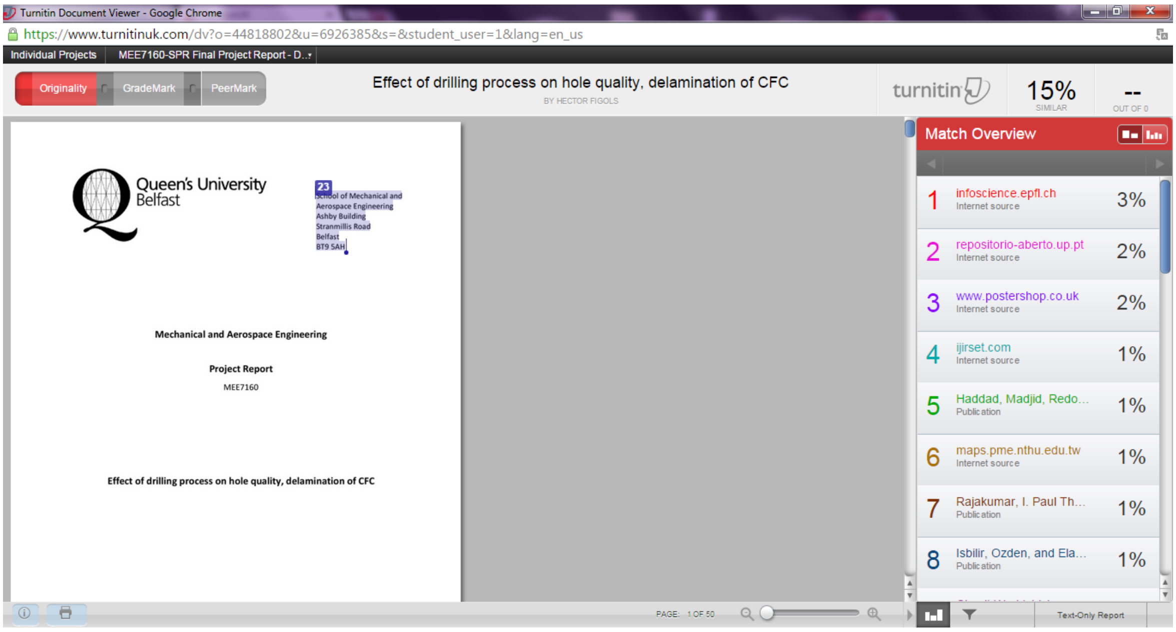


Figure 22. Screenshot of page 1 of the Originality Report Summary

Project Submission Checklist

	TICK IF MET
Does the report meet the formatting stipulated in the Module handbook and template provided?	X
Line Spacing (1.5)	X
Font (Calibri 11Pt)	X
Margins: Top & Bottom (25mm), Left (30mm), Right (25mm)	X
Paragraphs are fully justified	X
Does the main body of the report meet the strict 30 Page Limit (40 Page limit for MEE7012)? (excluding Title Page, Table of Contents, Turn-It-In Summary, References and Submission Checklist)	X
Do the Appendices meet the strict 10 Page Limit (15 Page Limit for MEE7012)?	X
Are all tables and figures numbered correctly, captioned and referenced if required?	X
Has the report been checked using Turn-It-In?	X
Is the Turn-it-in summary report included in the report?	X
Pages are numbered.	X

Statement of originality

I hereby declare that this project is my own work and that it has not been submitted for another degree, either at Queen's University Belfast or elsewhere. Where other sources of information have been used, they have been acknowledged.

Signature:

Date: 15/05/2015